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ORIGIN OF THE MOON: NEW DATA FROM OLD ROCKS

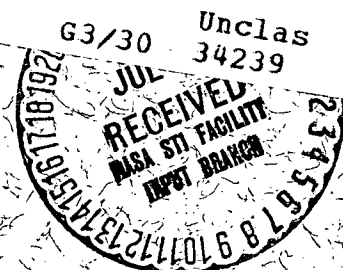
ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

BEVAN M. FRENCH

(NASA-TM-X-65924) ORIGIN OF THE MOON: NEW
DATA FROM OLD ROCKS B.M. French (NASA)
May 1972 103 p CSCL 03B N72-27886

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ORIGIN OF THE MOON:
NEW DATA FROM OLD ROCKS

Bevan M. French
Planetology Branch

May 1972

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

FRONTISPIECE

A crystal of pyroxene (Ca-Mg-Fe silicate) from an Apollo 12 lunar sample, photographed in polarized light. The color zoning in the crystal is produced by differences in chemical composition between the core and rim. The yellowish core is a Ca-poor, Mg-rich variety of pyroxene, while the reddish rim is a different variety of pyroxene that is enriched in Ca and Fe. These chemical differences show that the crystal grew in a molten silicate liquid that was progressively enriched in Ca and Fe as crystallization continued (see also Figure 38). Sample 12004; crystal is about 2 mm long.

PREFACE

This publication is an expanded version of a talk I gave to the Northeastern Regional Aerospace Education Conference in Orlando, Florida on July 24, 1971, two days before the launch of Apollo 15. In the talk, I attempted to describe some of the new knowledge about the moon, particularly that obtained from the Apollo 11 and Apollo 12 samples, in order to provide a framework for the impressive geological results that were to come out of the Apollo 15 mission. I hope that this published version will be useful in the same way, to provide background for the Apollo 16 and Apollo 17 missions and to provide an introduction to the scientific results to come from the post-Apollo period.

Because the results of each Apollo mission eclipse and modify the results of earlier ones, this is a poor time to attempt a general synthesis of the results of lunar studies. I have not attempted such a task here, nor have I attempted to describe the great quantity of information that has also come from the emplaced lunar experiments, orbital photography, and geochemical studies. Some of these results are listed briefly in the Appendix, and some sources to this area of research have been included in the Bibliography, with the hope that both the conclusions and the references will not be out of date by the time this document appears.

The Apollo program and the scientific results obtained from it have been due to the cooperative efforts of literally thousands of people, and even in this brief summary I am in debt to many individuals for their help. Thanks are due to Dr. Russell Rickert of West Chester College, Pennsylvania, one of the organizers of the Conference at which I gave the original talk, and to Dr. Louis S. Walter of the Planetology Branch at the Goddard Space Flight Center for his help as Principal Investigator on the Apollo samples. I am also grateful to my wife, Mary-Hill French, to my children, Sharon E. Childs and William T. Childs, to Kathleen A. Lavine, and to Dr. Paul D. Lowman for critical readings of early and late drafts of this manuscript. Finally, I am very much in the debt of many scientific colleagues, who supplied me, through both public and private communications, with much of the scientific information about the "new moon" that I have attempted to summarize here.

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ORIGIN OF THE MOON: NEW DATA FROM OLD ROCKS

INTRODUCTION

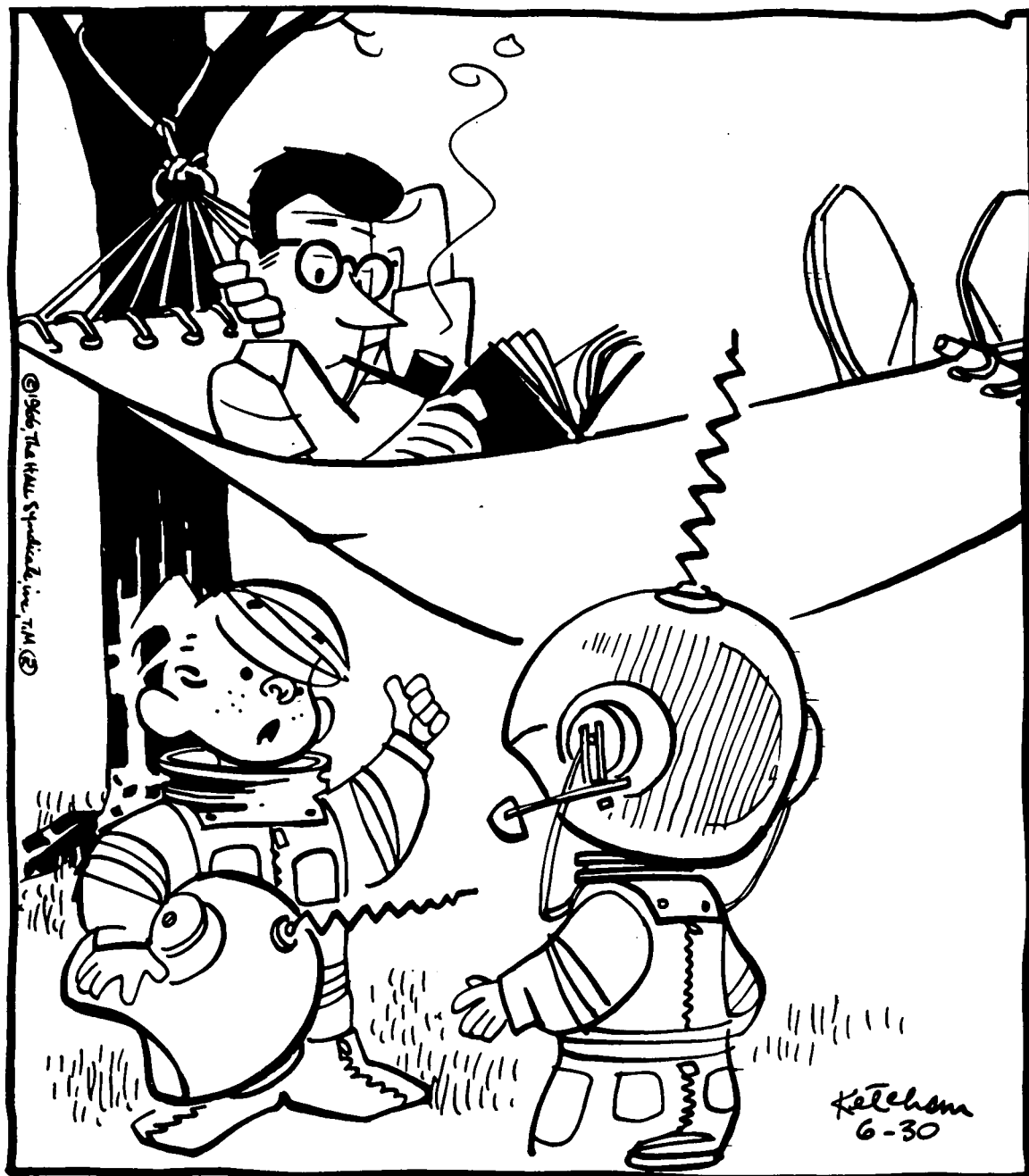
The origin and evolution of the moon is, and has always been, a complex and much-debated subject, and it has continued to be so in the light of the data returned by the Apollo program. What we have obtained from the Apollo program is a tremendous amount of new data and knowledge which we could not have obtained in any other way. In particular, the information which we have obtained by studying the returned lunar samples represents a breakthrough in the study of the moon which is comparable to the first use of the telescope by Galileo to examine the moon almost 400 years ago.

The Apollo results are only the latest and most spectacular in a long history of human study of the moon. They are the apex of a huge pyramid of human study and effort, and, even as they are built on past studies, so they will become the foundations for future investigations. Like Galileo's examination of the moon by telescope, the Apollo data have raised more questions than they have answered, but as we have learned more about the moon, we can now speak a little more confidently about its origin and history. Even if the answers are not yet definite, some things are becoming a little more certain and the problems themselves are becoming better understood.

To start with, I will summarize the pre-Apollo and Apollo history of lunar exploration. Second, I will discuss one facet of the Apollo results in which I am involved, namely, the study of the lunar rocks, the determination of their minerals and chemistry, and the attempt to use these data to reconstruct the conditions under which these rocks formed. Finally, I will summarize the new picture of the moon as we look at it from the vantage point of the Apollo results.

A brief review of the pre-Apollo period is important, partly to place the Apollo results in the context of earlier work, and partly because so much has happened in the last few years that an occasional review is helpful to us all. It is startling to realize that so much exploration and discovery has been compressed into the last ten years, and many of us feel sometimes like the characters in Figure 1.

Our subject, the moon, is shown in Figure 2 as seen from earth, as it has been seen by man during all but the last few years of his million-year-long history. It looks the same here as it would have looked through Galileo's telescope,



"AN' YA KNOW WHAT? ... WHEN MY DAD WAS LITTLE THEY DIDN'T EVEN HAVE **SPACE!**"

Figure 1. Drawing by H. Ketcham. Copyright 1966 by Publishers Hall Syndicate. Used by permission.

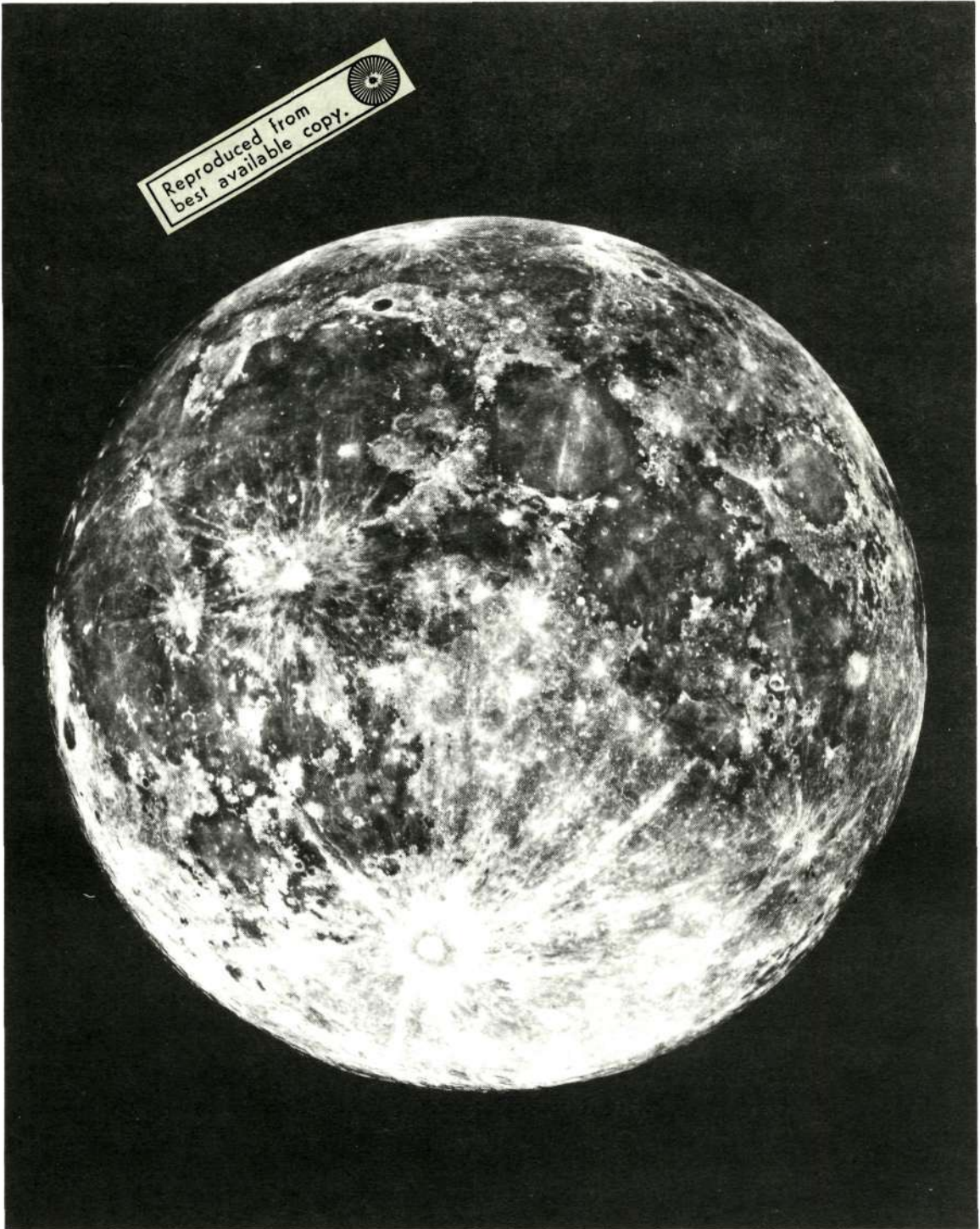


Figure 2. View of the full moon, showing the division into bright highland areas and dark mare basins. The large bright-rayed crater at the bottom is Tycho.

and it is important to remember that most of the questions he asked are still with us, generally unanswered:

1. What causes the division into the light-colored rugged highlands and the darker, flat areas which he thought were actual seas and which we still call maria? (Singular, mare.)
2. What is the origin of the large bright rayed craters such as Copernicus and Tycho?
3. And the greatest and most important question, why is it there at all? As you probably know, the earth-moon system is unique in the solar system because the moon is so large in comparison to the earth, and the earth-moon system has often been described as a "double planet." The only moons similar in size to ours revolve around huge planets like Jupiter and Saturn. Smaller planets like the earth, when they have moons at all, have only small bodies a few miles in diameter, like the two that circle Mars.

Gradually, as scientists continued to wonder about the moon and about the history of the earth-moon system, three main theories for the origin of the moon developed, all of which have survived, in varying degrees, the new testing given them by the Apollo data (Figure 3). Theory 1, the so-called "daughter" theory, holds that the moon was part of the earth and then separated from it at some time in the past when both of them were molten. Theory 2, called the "sister" theory, suggests that the moon and earth developed as a double planet during the original condensation of matter that formed the solar system and that they have remained a double planet ever since. Finally, Theory 3, which one might call the "pick-up" or "mistress" theory, argues that the moon formed somewhere else, perhaps even outside the solar system, and that it passed by the earth and was captured by it at some time in the past.

All the theories have their own problems and defects, and none of them has been generally accepted. In fact, some of the problems are so serious that at least one prominent scientist has commented that, if he had to judge the origin of the moon on the basis of which theory was most plausible, he would have to insist that it wasn't there at all!

As you might expect, when there is uncertainty and debate about the origin of the moon, there is similar argument about the origin of most of its surface features. One of the greatest arguments has centered on the origin of the many large craters that are scattered across the moon's surface. Two chief theories have emerged; first, that the craters were formed by impacts of very large

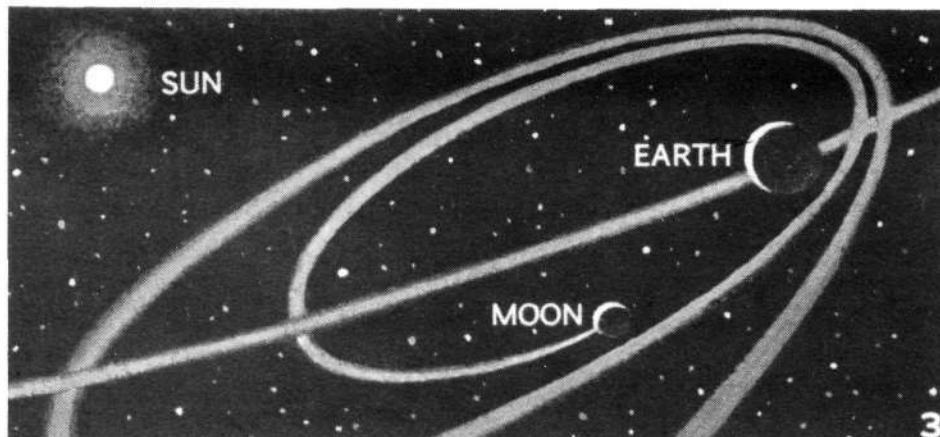
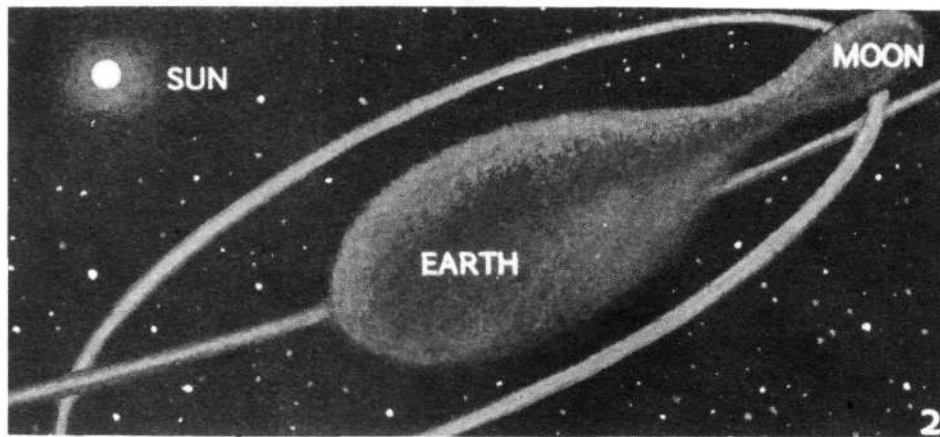
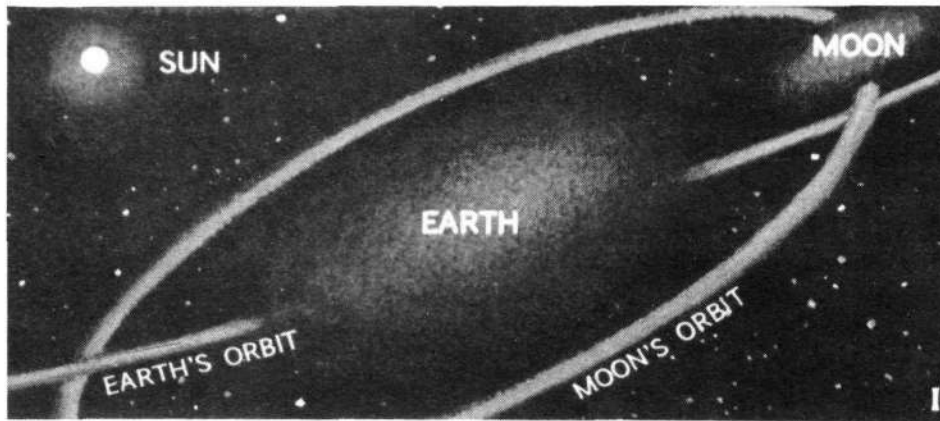


Figure 3. Artist's versions of three possible origins for the moon: (1) separate formation at the same time as the earth (top); (2) separation of the moon from the earth (center); (3) capture of the moon by the earth (bottom). Paintings by Davis Meltzer from the February, 1969 issue of National Geographic Magazine. Copyright 1969 by the National Geographic Society; used by permission.

meteorites and asteroids on the moon, and second, that the craters formed by internal volcanic eruptions, as do similar large craters on earth.

The moon is a complex and diverse place, and proponents of both theories can find evidence to support them, depending on which crater you look at. Copernicus (Figure 4) has long been considered to be a typical impact crater, and scientists have argued that the ejection of large amounts of material (ejecta) during a huge impact event has formed the rubbly, irregular surface around the crater and the bright streaks of materials (rays) that extend radially from it. By contrast, other scientists who favor the volcanic hypothesis point to craters like Plato (Figure 5), which is filled with dark material resembling the mare lavas, and they suggest that such an appearance is typical for a crater formed by volcanic action.

Another major area of discussion has concerned the origin of the elongate depressions (sinuous rilles) that look very much like river valleys. A typical group of such rilles near the crater Prinz is shown in Figure 6. Three main origins have been proposed. First, that the rilles were formed by actual erosion by water during a period in the past when the moon had sufficient atmosphere to sustain, even briefly, the presence of liquid water on its surface. (This theory, incidentally, has been greatly weakened by the complete absence of any water in the returned Apollo samples.) A second theory holds that the rilles were cut by dense flows of gas-laden volcanic ash particles poured out in volcanic eruptions similar to that of Mont Peleé in Martinique in 1902. A third theory, also volcanic, suggests that the rilles are collapsed lava tunnels through which molten rock flowed to spread out over the maria as lava flows. One of the major goals of Apollo 15 was to study one of these sinuous rilles, Hadley Rille, on the ground, and to bring back information which might allow us to decide between these different origins.

A REVIEW OF MODERN LUNAR EXPLORATION

After Galileo, study of the moon continued for several hundred years with more sophisticated telescopes, observations, and mathematical models. The present modern period of lunar exploration began with the commitment made by President Kennedy on May 25, 1961, "before this decade is out, of landing a man on the moon and returning him safely to earth," a commitment fulfilled by the landing of Apollo 11 on the Sea of Tranquillity on July 20, 1969.

Most people believe that the intensive study of the moon in the pre-Apollo period began with the Ranger missions. Actually, the first major study of the moon to prepare for the Apollo landings was a detailed program of geological mapping of the moon by telescope carried out by the U.S. Geological Survey.

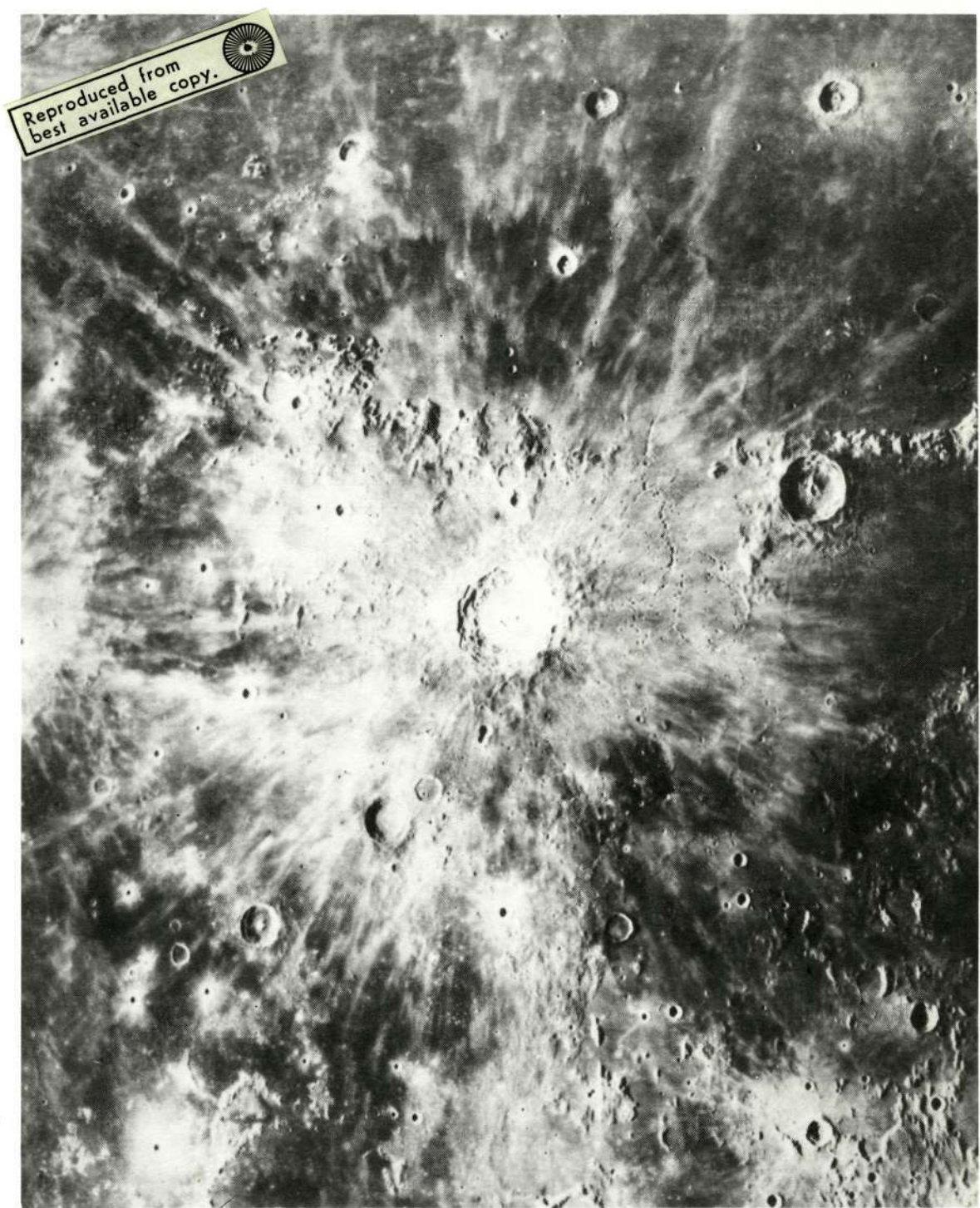


Figure 4. An earth-based telescopic photograph of the large bright-rayed crater Copernicus, which is about 50 mi in diameter. This view shows the widespread distribution of ray material and a line of very small secondary craters between Copernicus and Eratosthenes, the large crater at the right edge of the photograph.



Figure 5. Large circular crater Plato (upper left), as seen in an Earth-based telescopic photograph. The crater is filled with dark material that is probably lava flows. The light-colored mountains in the center of the picture are the Apennines. The darker smooth material at lower left is the surface of Mare Imbrium; Mare Frigoris is the dark area at the top of the picture.

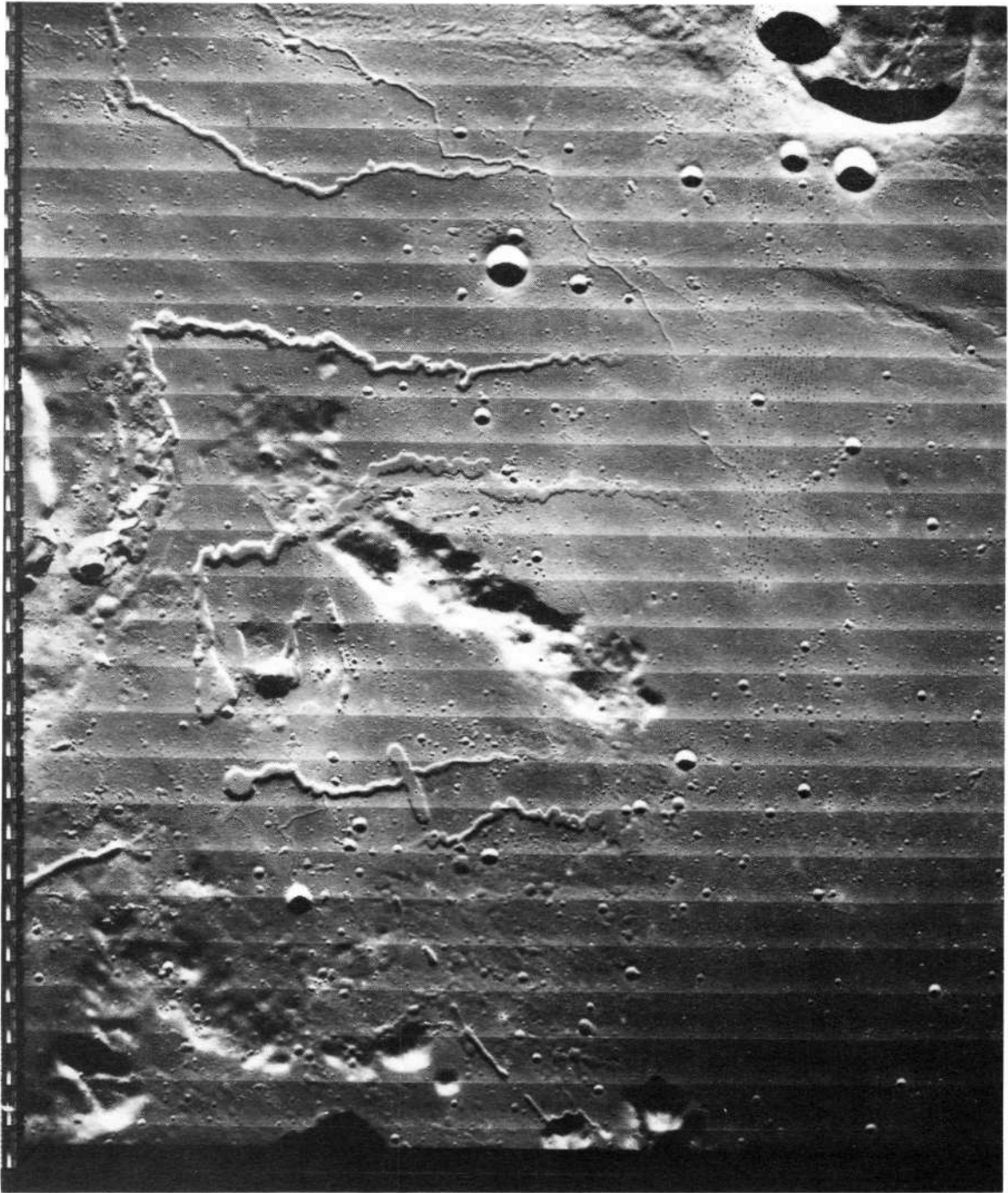


Figure 6. A group of lunar sinous rilles near the crater Prinz as seen by Lunar Orbiter. Note that many of the rilles begin in craters or depressions (at left side) and flow out onto the mare without leaving any apparent deposits or delta at their lower end. NASA photograph V-191-M.

Geologists, from their long study of the earth, have developed various methods for telling the relative ages of different rock units or formations. While the actual techniques are fairly complicated, most of the principles are relatively simple. For instance, if one layer overlies another, the layer above is the younger. Or if a body of once-molten rock cuts or intrudes other rock, the cross-cutting body is the younger. By using these principles, and by observing such details as color, surface texture, and albedo (the amount of light reflected) on the lunar surface, the U.S. Geological Survey was able to produce a geologic map of the whole moon to plan the Apollo missions.

This mapping was necessary for several reasons. First, it provided a framework of relative ages for the different rock units on the moon into which determinations of the absolute ages of returned samples could be fitted. Secondly, the geologic mapping was necessary in order to identify the most scientifically important sites to be visited by the Apollo landings.

One example of such a lunar geologic map is shown in Figure 7, which is the landing area for Apollo 15 near Hadley Rille. Each color refers to a different unit or formation, and the observed relations between different units allow geologists to arrange the formations in order of relative age. The oldest rocks recognized are the lighter gray units that form the Apennine mountains in the SE part of the map. These are believed to be rocks present before the great meteorite impact that formed Mare Imbrium to the NW and raised the Apennine Mountains around its rim. Other units in this area are believed to be material ejected when the Imbrian basin was formed and deposited on the older (pre-Imbrium-basin) rocks.

The large crater in the NW corner is Archimedes. The darker-gray unit around it, identified as ejecta from the crater, covers both the older Apennine rocks and the Imbrian ejecta. These relations tell us that Archimedes must have formed after Mare Imbrium. Indeed, such a relatively small crater would not have survived the huge Imbrian event if it had been present. However, the ejecta blanket is not present around the whole crater. In the north, east, and west, it is apparently overlain by younger dark units of mare material, which we believe are therefore younger than the crater Archimedes.

Even this simple examination tells us something very important about lunar history. We see that the large crater Archimedes formed after the impact that made the basin of Mare Imbrium, but before that basin was filled by lava flows. Therefore, there must have been a definite interval of time between formation of Mare Imbrium and its filling with lava flows, long enough for several large craters like Archimedes to form. We can't tell exactly how long that interval was just by looking at the moon. However, the relations shown here are

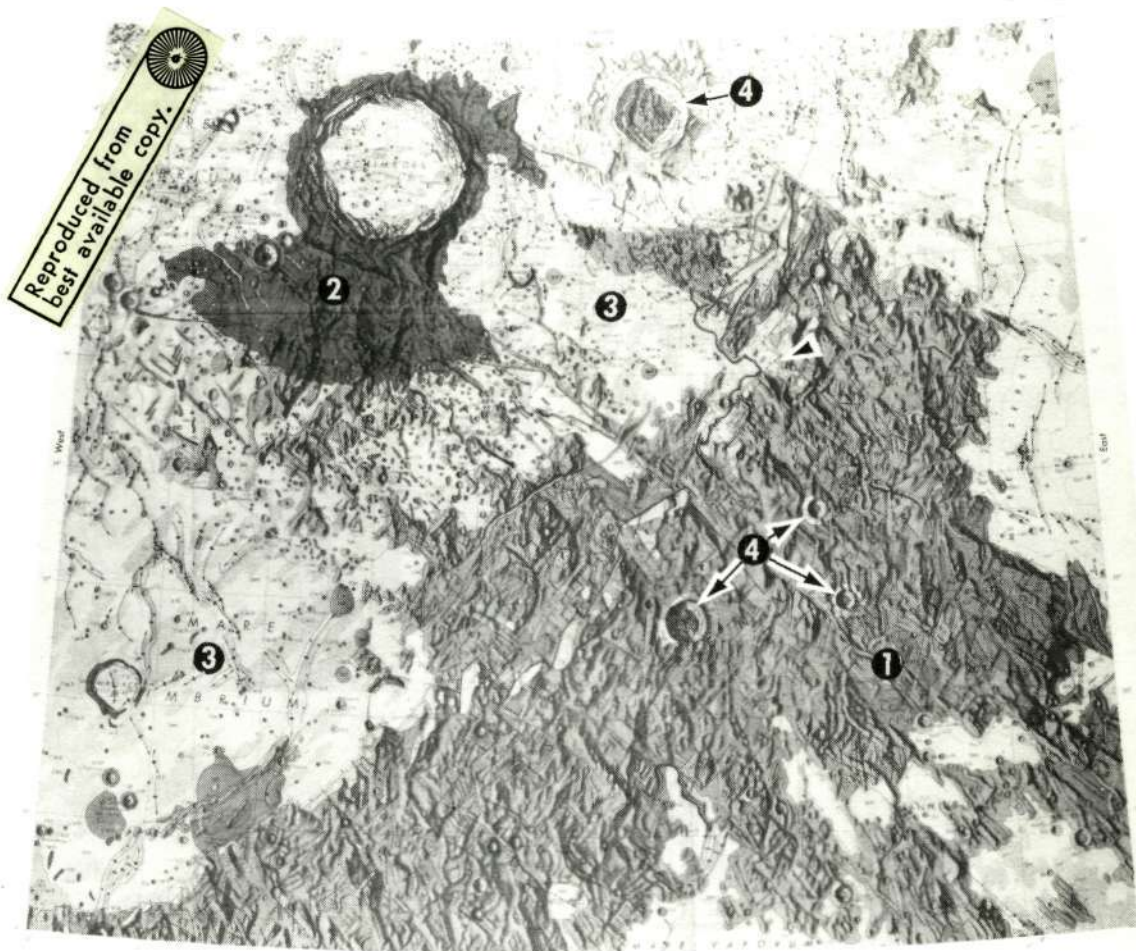


Figure 7. Lunar geologic map of the Hadley-Apennines region of the moon near Mare Imbrium. The major rock units, from oldest to youngest, are: (1) pre-Imbrium-basin rocks that form the Apennines mountains (medium-gray); (2) ejecta deposits from craters formed after the Imbrium basin, such as Archimedes (dark gray); (3) lavas that fill Mare Imbrium (light gray and white); (4) ejecta deposits from younger impact craters (shown by arrows). The Apollo 15 landing site at Hadley Rille is shown by an arrow. The rilles (dark sinuous lines) are about the same age or slightly younger than the mare-filling lavas. Map is taken from the publication, Geologic map of the Montes Apenninus region of the moon, by R. J. Hackman, U.S. Geological Survey Map I-463 (LAC-41), 1966.

strong evidence against the idea, suggested by several scientists, that the mare basins were filled immediately upon formation by molten rock produced or released by the impact event itself.

Even younger rock units can be recognized on the map. There are many long sinuous rilles, one of which is Hadley Rille, winding across the surface of the lava flows that fill the maria, and the rilles must be the same age or younger than the flows in which they are found. Definitely younger than the mare flows are the small fresh craters with completely circular ejecta blankets, which have been formed since the mare lavas solidified.

Even this brief look at the Apollo 15 landing site shows the great power of these geological methods. Just by observing from the earth, one can recognize at least four different rock units and can arrange them in order of relative age. From oldest to youngest, they are: (1) the pre-Imbrian rocks which form the Apennine mountains; (2) the ejecta from the Archimedian craters formed after the mare basins and before they were filled; (3) the mare lavas and the sinuous rilles; (4) the younger impact craters formed on the mare surface. These observations also establish the existence of a significant time interval between formation and filling of Mare Imbrium. Finally, and most important, these geological observations provide a relative time scale into which age determinations on the returned samples can be fitted to produce an absolute-age history for the entire moon.

An artist's view of the history deduced from these geological observations (Figure 8) shows the stages of development of the Mare Imbrium region of the moon. From top to bottom, these are, progressively: (1) the impact of an asteroidal projectile to form the mare basin; (2) the formation of Archimedes and other large craters during the interval between formation of the basin and its filling by lava flows; (3) the actual outpouring of molten lava that filled the basin; (4) finally, a long period of relative quiet, with formation of younger craters and gradual erosion to form the moon as we see it today.

While this geological basis for lunar exploration was being developed, a series of unmanned probes were sent to the moon, the Ranger, Surveyor, and Orbiter spacecraft. These different spacecraft had two chief aims: (1) to obtain high-resolution photography of the moon in order to plan the Apollo missions and select the landing sites; (2) to detect hazards that might be invisible from earth. Many of these probes were so successful in fulfilling their chief aims that a large number of the later flights were devoted to scientific observations and overall lunar mapping.

The Ranger spacecraft, which were to transmit back television pictures of the moon before crashing into it, were first launched in 1961 and first succeeded with Ranger VII in 1964. One of the more spectacular views returned by this program is the view that Ranger IX sent back of the crater Alphonsus (Figure 9). This picture shows the crater itself, the elongate central peak, and the numerous dark-halo craters that many people think were produced by volcanic activity. You can also just begin to see the appearance of large numbers of small craters on the crater floor, most of which are too small to be seen from earth.

The Ranger photographs increased the resolution of lunar observations by a factor of 1000. From the earth, the best telescopes can recognize objects about a kilometer across on the lunar surface. In the Ranger pictures, small craters

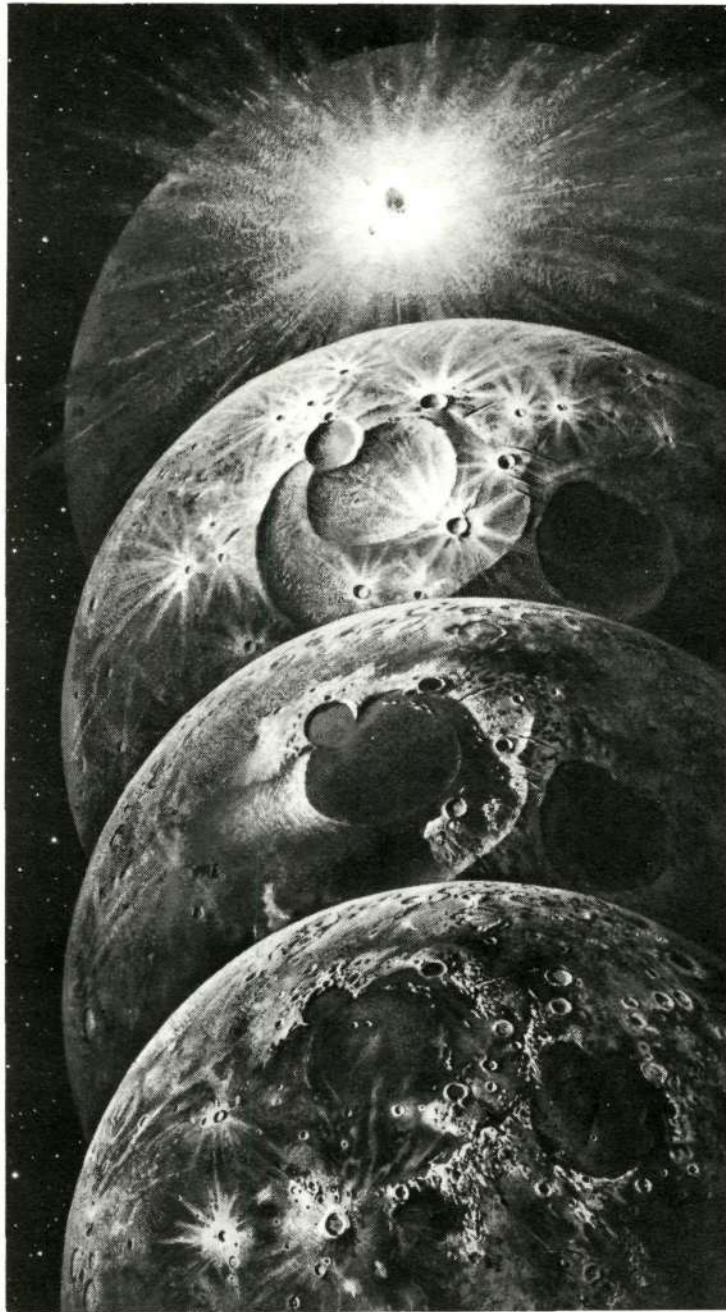


Figure 8. Artist's version of the history of Mare Imbrium and the surrounding region as deduced from geological mapping. From top to bottom, the sequence is: (1) impact of a large asteroid to form the Mare Imbrium basin; (2) a long interval with formation of other large impact craters around the basin; (3) flooding of the mare basin by extensive lava flows; (4) formation of younger impact craters, together with general erosion by meteorite bombardment, to form the surface of the moon seen today. Painting by Davis Meltzer from the February, 1969 issue of National Geographic Magazine. Copyright 1969 by the National Geographic Society; used by permission.

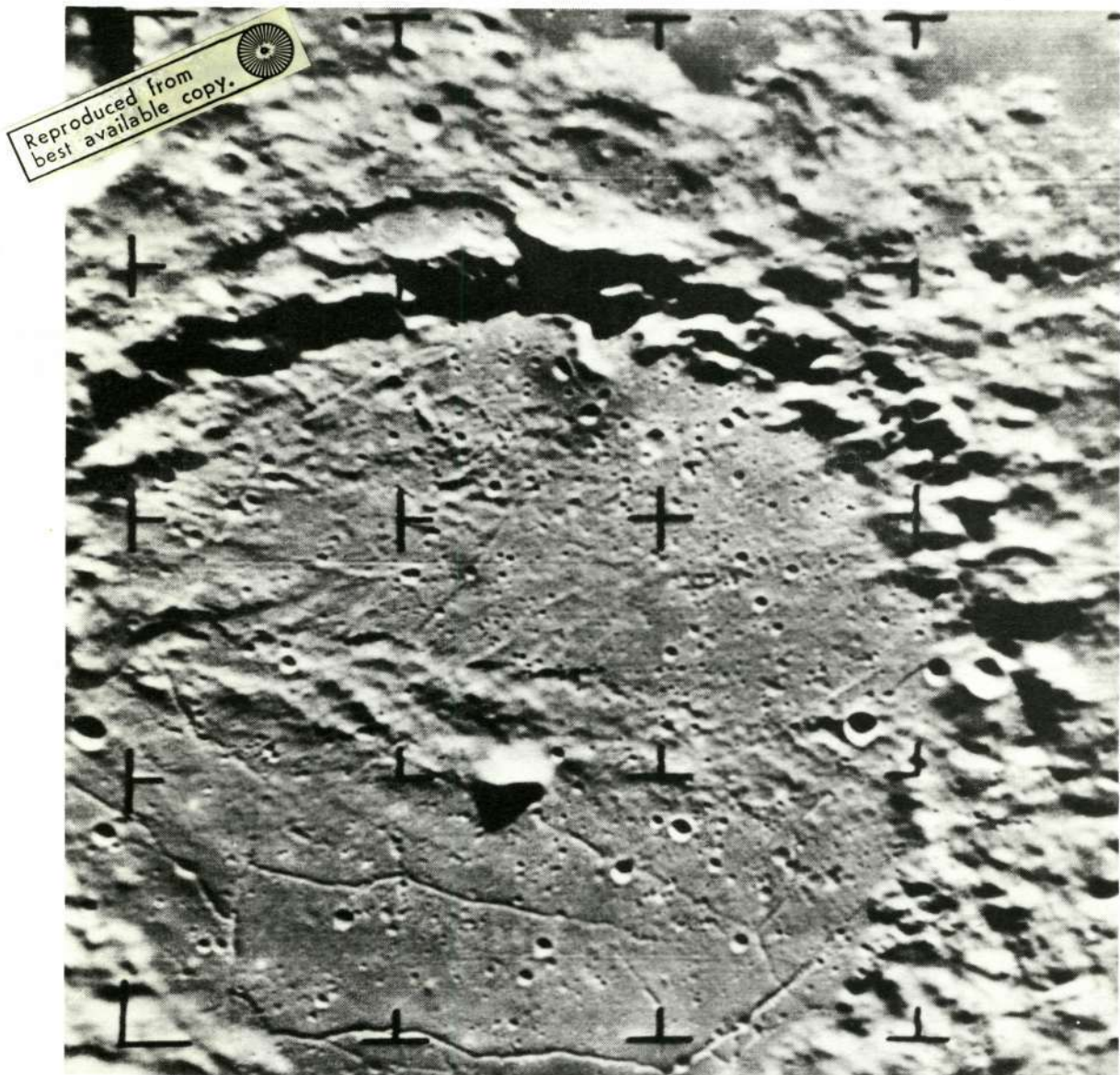


Figure 9. Ranger 9 TV photograph of the crater Alphonsus, transmitted before the spacecraft crashed into the crater. The main features of Alphonsus are clearly visible: the elongate central ridge, the fractures around the floor, the unusual dark-halo craters at the right side, and the numerous small craters on the floor.

as little as a meter across were detectable, and one major result of the Ranger program was the realization that the surface of the moon was literally saturated with such small craters, apparently produced by the continual bombardment of small particules over a long period of time.

The Surveyor program provided a further increase in resolution by another factor of 1000. The Surveyors were designed to make soft landings on the lunar

surface and to transmit back television pictures in which objects as small as a millimeter across could be recognized. The program began with a spectacular success as Surveyor 1 softlanded on the moon on May 30, 1966, remained on the surface, and began to transmit back pictures of its surroundings, such as the panoramic view shown in Figure 10, in which the shadow of the spacecraft itself stretches across a rock-strewn expanse of lunar soil.

In those few brief moments, the main aims of the Surveyor program were achieved. Surveyor 1 demonstrated for the first time that the lunar surface, although composed of a mixture of rock and mineral fragments, would support men and machinery for later landings. There was no layer of deep dust to swallow up spacecraft and astronauts, and the surface was such that men could walk and work on it. Another discovery, this one of great importance to geologists, was that there were indeed rocks resting on the lunar surface (Figure 11), waiting for the time when man could get to them and study them.

Later Surveyor spacecraft did much more. They sent back thousands of photographs of various landing sites. They showed close-up views of boulders such as the large white-spotted rock shown in Figure 12, so that geologists could start to draw conclusions about their structure and origin. They conducted various digging and trenching experiments to provide detailed information about the nature of the soil. And finally, in 1967, Surveyor 5 performed, in Mare Tranquillitatis, the first chemical analysis of the surface of another planetary body. The remote analysis indicated that the site was underlain by basaltic rocks, a conclusion fully confirmed by the Apollo 11 results two years later.

While the various Surveyors were exploring the lunar surface, the Orbiter spacecraft above them were photographing the moon from lunar orbit. The main goal of the five Orbiter spacecraft was to provide good high-resolution photography of the possible Apollo landing sites. The program was the most successful in unmanned lunar exploration; five spacecraft were launched and five were successful. The immediate aims of the program were achieved so early that the later spacecraft could be used for general mapping of the lunar surface. Many thousands of high-resolution photographs were returned, so many that a large room is required just to store them, and containing so much information that they will keep scientists busy studying them for years.

One major unexpected result of the Orbiter program was obtained simply by tracking the spacecraft as they went around the moon. Analysis of slight deviations in their orbits led to the discovery of concentrations of mass (mass-cons) located under the lunar maria. This recognition that the mass distribution on the moon is not uniform and that the maria are underlain by denser rocks than the surrounding highlands is still not fully understood, but it was one of the

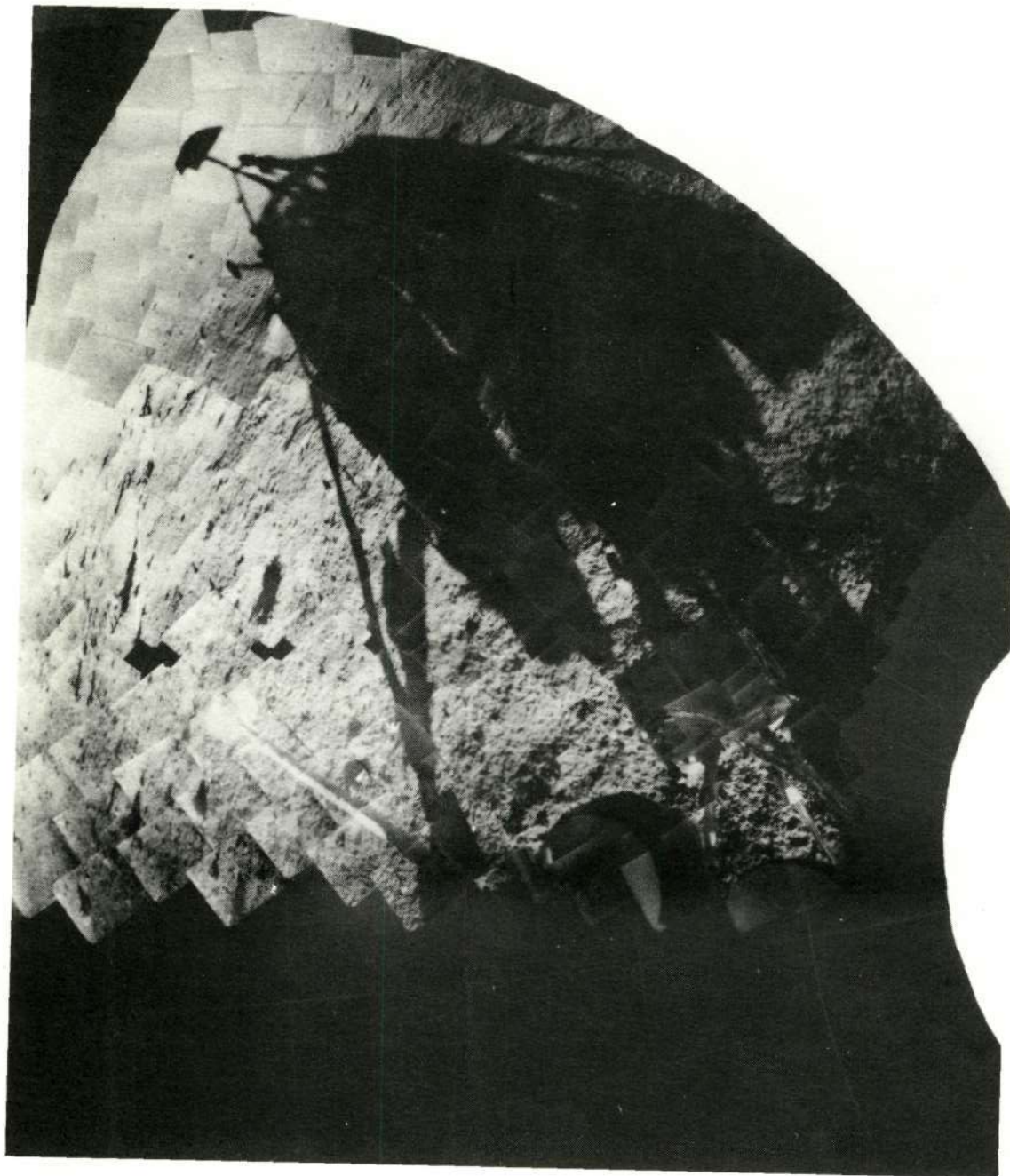


Figure 10. Panoramic view transmitted by the Surveyor 1 TV camera after a successful soft-landing on the lunar surface. NASA photograph 66-H-825.

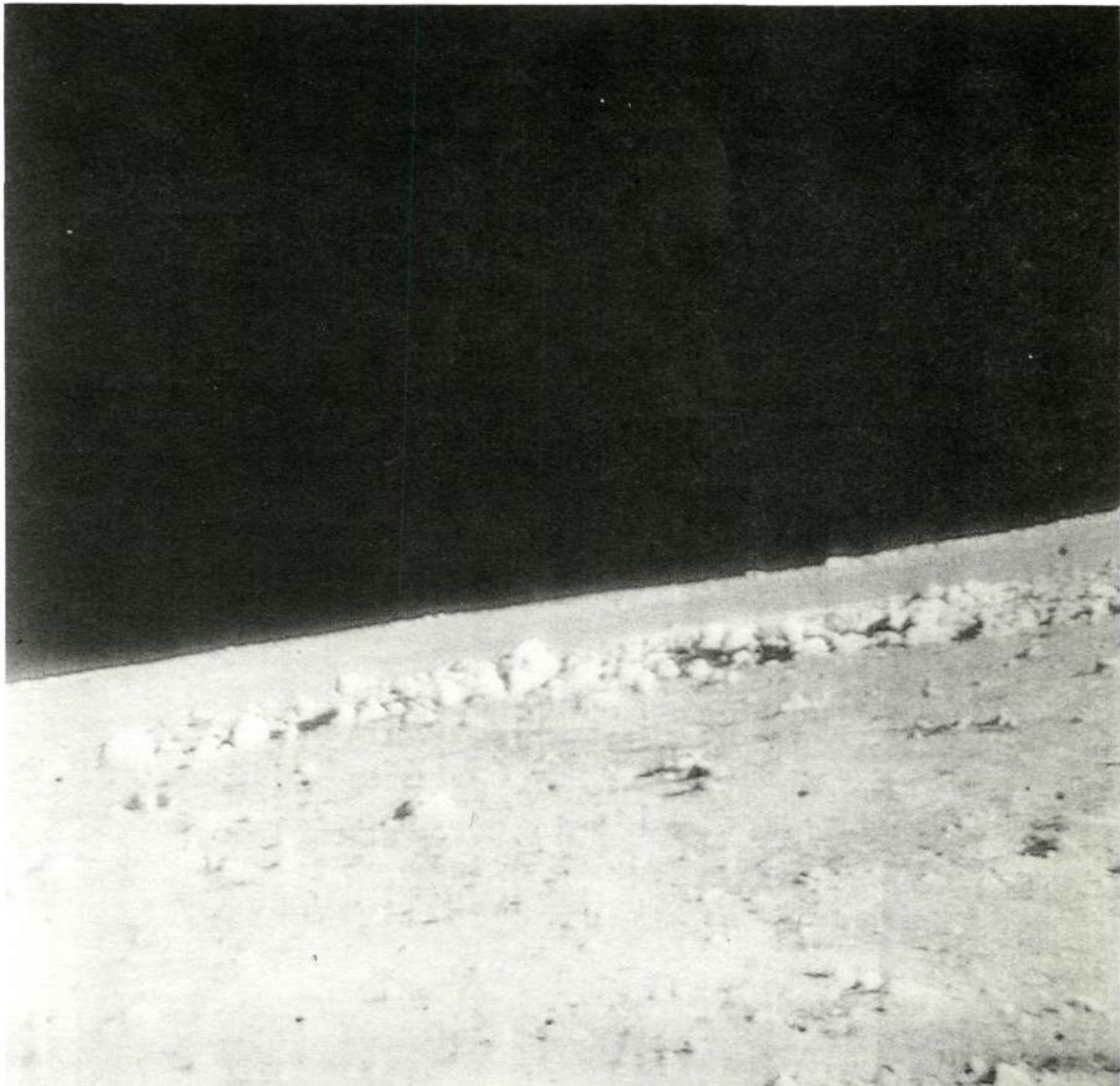


Figure 11. A rock field seen by the TV camera on Surveyor 1. The concentration of rocks marks the near rim of a moderate-sized crater. The far rim of the crater can be seen as a similar line of rocks on the horizon. NASA photograph 66-H-807.

most important scientific discoveries about the moon before the Apollo landings themselves.

Finally, the Orbiters provided so much spectacular landscape photography of the moon that they produced a real change in our viewpoint of the moon. As we looked at the Orbiter pictures, the moon was no longer a distant body in the sky, but it was now a planetary surface above which one could fly and observe, much as one might observe the earth from an airplane or an orbiting spacecraft.

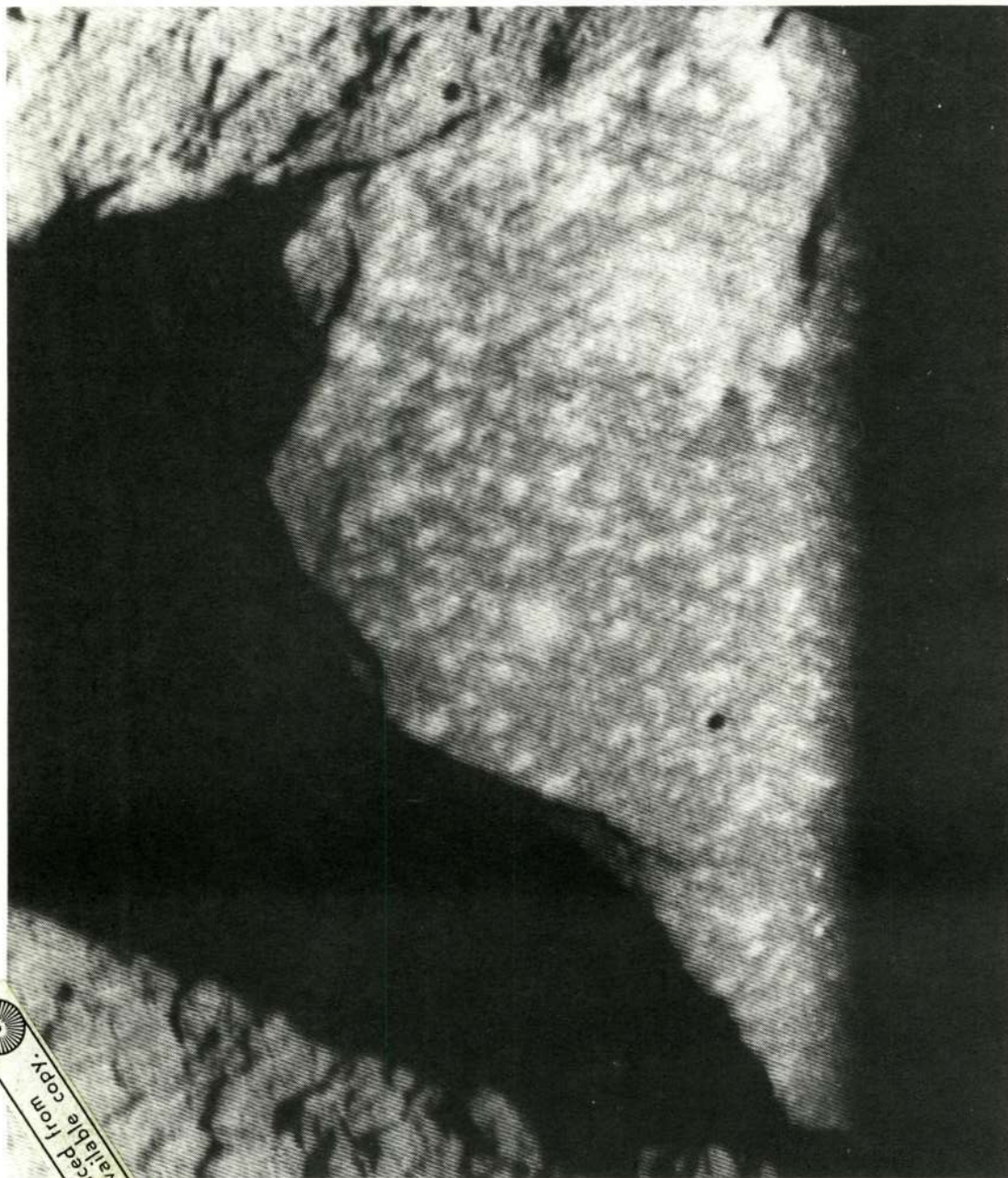


Figure 12. Closeup view of a large white-spotted boulder about a foot across seen by the TV camera in Surveyor 7, which landed near the crater Tycho. The rock is probably a breccia containing fragments of light-colored feldspar-rich material. NASA photograph 68-H-147 (VII-W-54).



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A few of the more spectacular pictures will serve to indicate the success of the Orbiter program in bringing the moon closer and making it more familiar. In Figure 13, we look out over Oceanus Procellarum from above the neighboring highlands, seeing the flat dark maria surface and the impressive linear "wrinkle ridges" along the surface. In Figure 14, we are approaching the crater Copernicus from a low angle; you can see Copernicus on the horizon, with the oddly-shaped crater Fauth in the foreground. Finally, in Figure 15, which has been called "The Picture of the Century," we look across the crater Copernicus from above its rim. The picture shows the 2-mile-high terraced walls and the long central peak. The Orbiter pictures have made even typical impact craters like Copernicus seem slightly more volcanic. Along the far wall there are rocks resembling lava flows that may have poured down the crater walls from the terraces, and in the central peak there is a dark streak which some have suggested is an intrusive lava dike.

Better evidence for the existence of volcanism on the lunar surface is seen in an Orbiter photograph of the Marius Hills (Figure 16), near the crater Marius. This area of low domes and rounded hills is very suggestive of volcanic areas on the earth, and some of the rock units in this area have been tentatively identified as lava flows. Because of its abundant evidence for volcanic activity, the area was a possible landing site for Apollo 17.

The Orbiters also provided the first detailed view of the "back" side of the moon, the side which is invisible from earth. Here is the first complete view of Mare Orientale (Figure 17), located on the border between front and back sides. The bull's-eye structure is about 600 mi across, and is believed to be the youngest of the mare basins. Although it is not much smaller than Mare Imbrium, it contains very little dark mare material except for the patchy areas in the center. This observation indicates that, when Mare Orientale formed, conditions within the moon must have been sufficiently different so that no great outpouring of lava to fill the basin occurred.

One result of these observations of the back side of the moon was the discovery that most of the dark mare-filling material, which is probably all lava flows, is concentrated on the front side of the moon, while the back side is dominantly composed of lighter, heavily-cratered highlands-type material. One of the few small areas of mare-like material on the back side of the moon is the crater Tsiolkovsky (Figure 18), about 150 mi in diameter. One interpretation is that the crater itself was formed by a large impact and then filled with internally-produced lava, like Mare Imbrium but on a smaller scale.

Finally, with the Ranger, Surveyor, and Orbiter programs complete, we had learned as much about the moon as we could by sending machines. It was

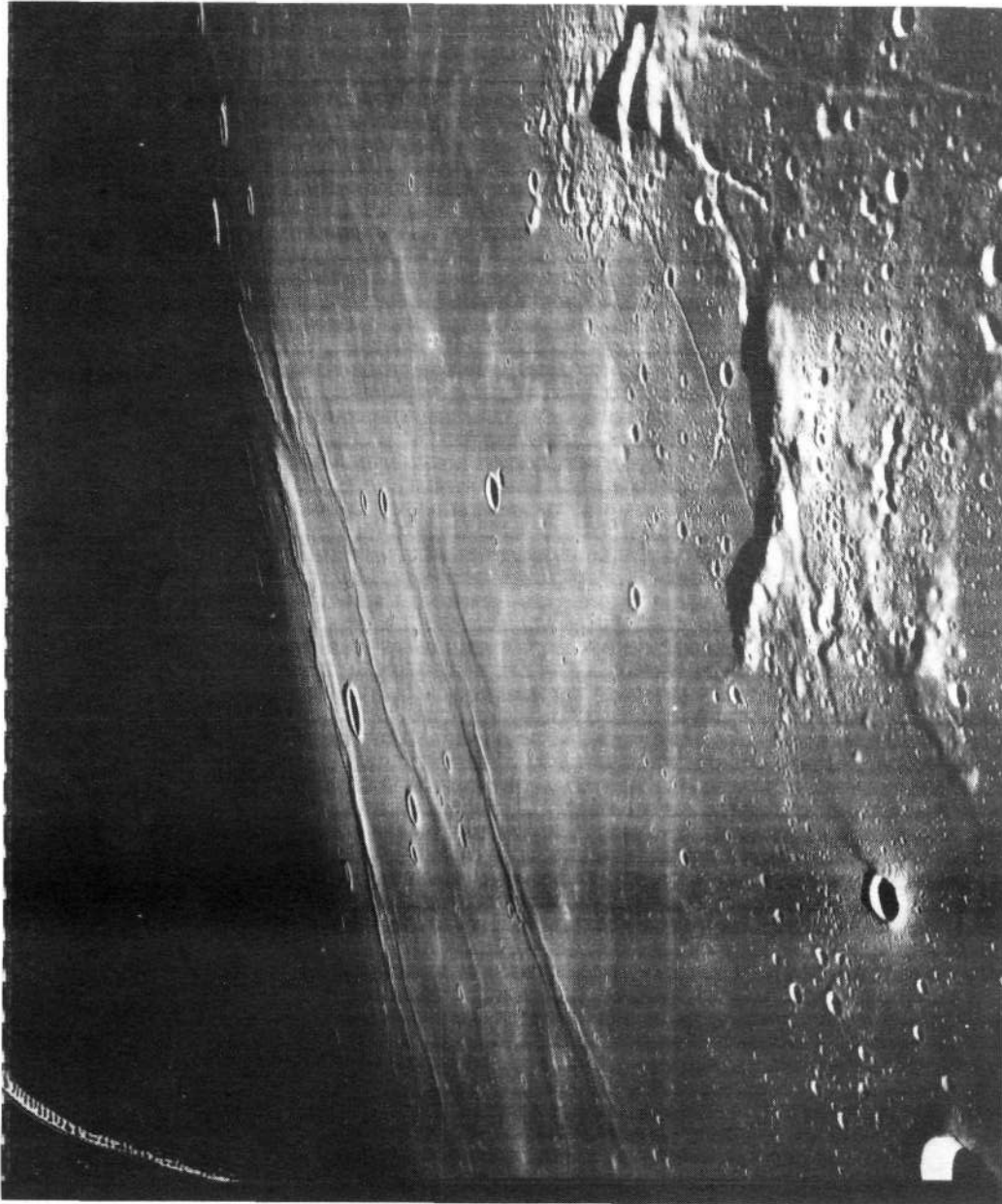


Figure 13. View of dark mare material on Oceanus Procellarum as seen by Lunar Orbiter 3. This low-angle view shows older, more heavily-cratered rocks along the shore of the mare (lower right) and the relatively smooth surface of the mare itself. The linear features in the mare are "wrinkle ridges" which have probably been produced by deformation of the partly-solidified lavas during flow. NASA photograph III-161-M.

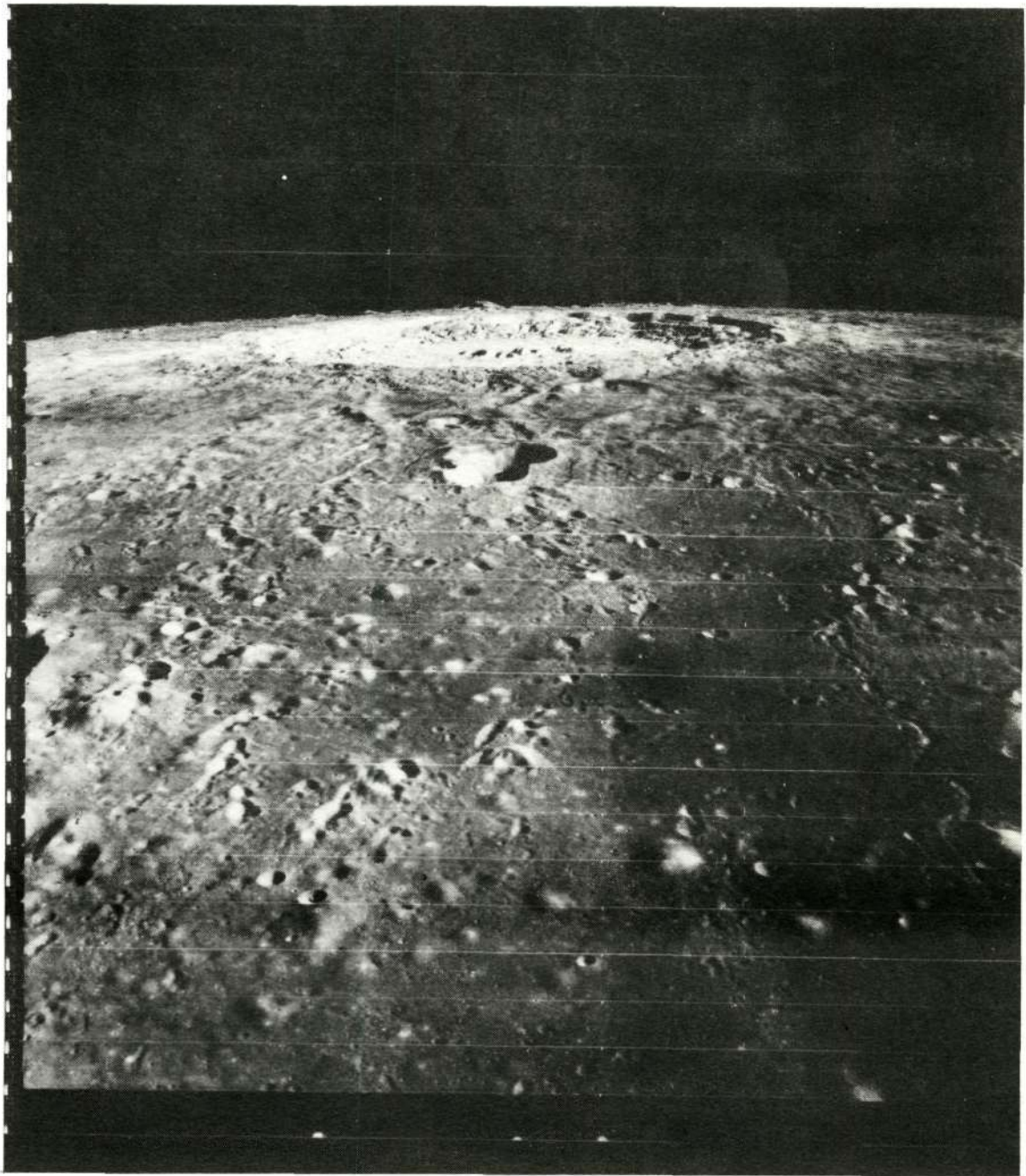


Figure 14. Low-angle Orbiter 2 photograph showing the terraced crater Copernicus on the horizon. The crater is about 50 mi in diameter. The unusual double crater in the upper center of the picture is Fauth. NASA photograph 11-162-M.

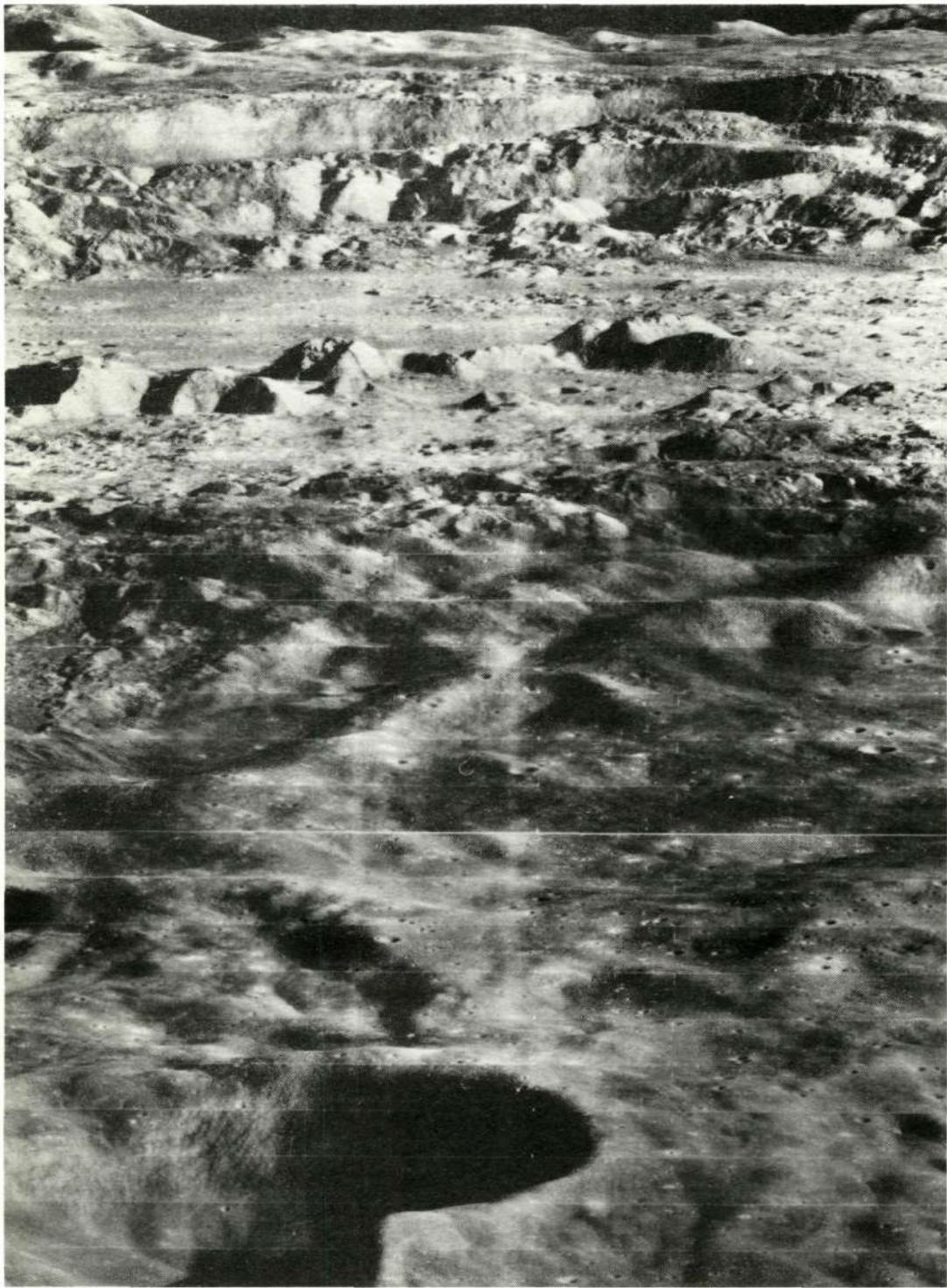


Figure 15. Orbiter 2 view of the inside of the crater Copernicus, taken from just above its rim. The crater in the foreground is the double crater Fauth (see Figure 14). The central peak of Copernicus appears as a line of mountains. The terraced walls of Copernicus beyond the central peak are about two miles high. NASA photograph II-162-H.

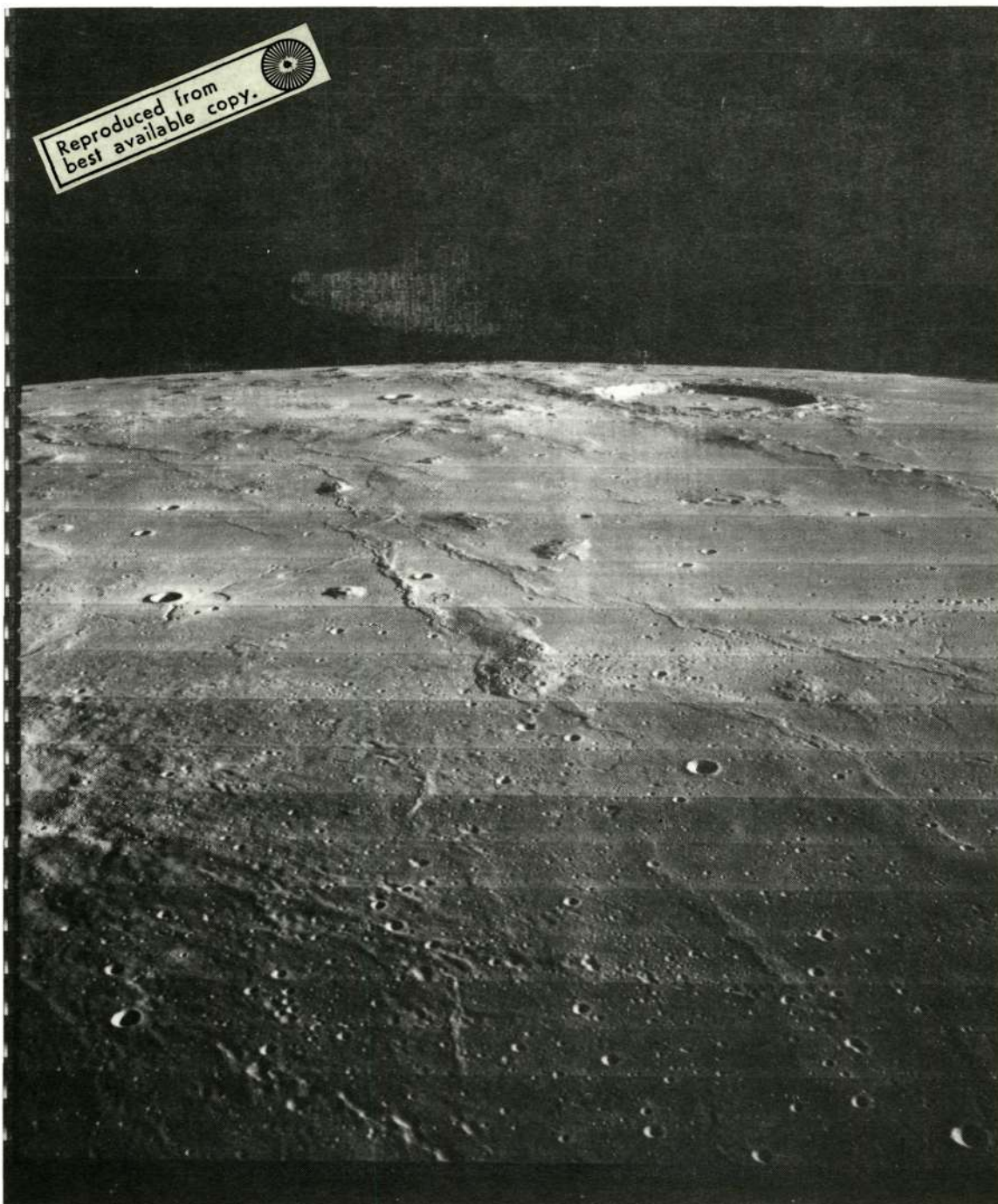


Figure 16. Possible volcanic features near the crater Marius (large crater at upper right) seen by Orbiter 2. The numerous domes and low hills (Marius Hills) in the center of the photograph are thought to be of volcanic origin and are very similar to terrestrial volcanic features. NASA photograph II-213-M.

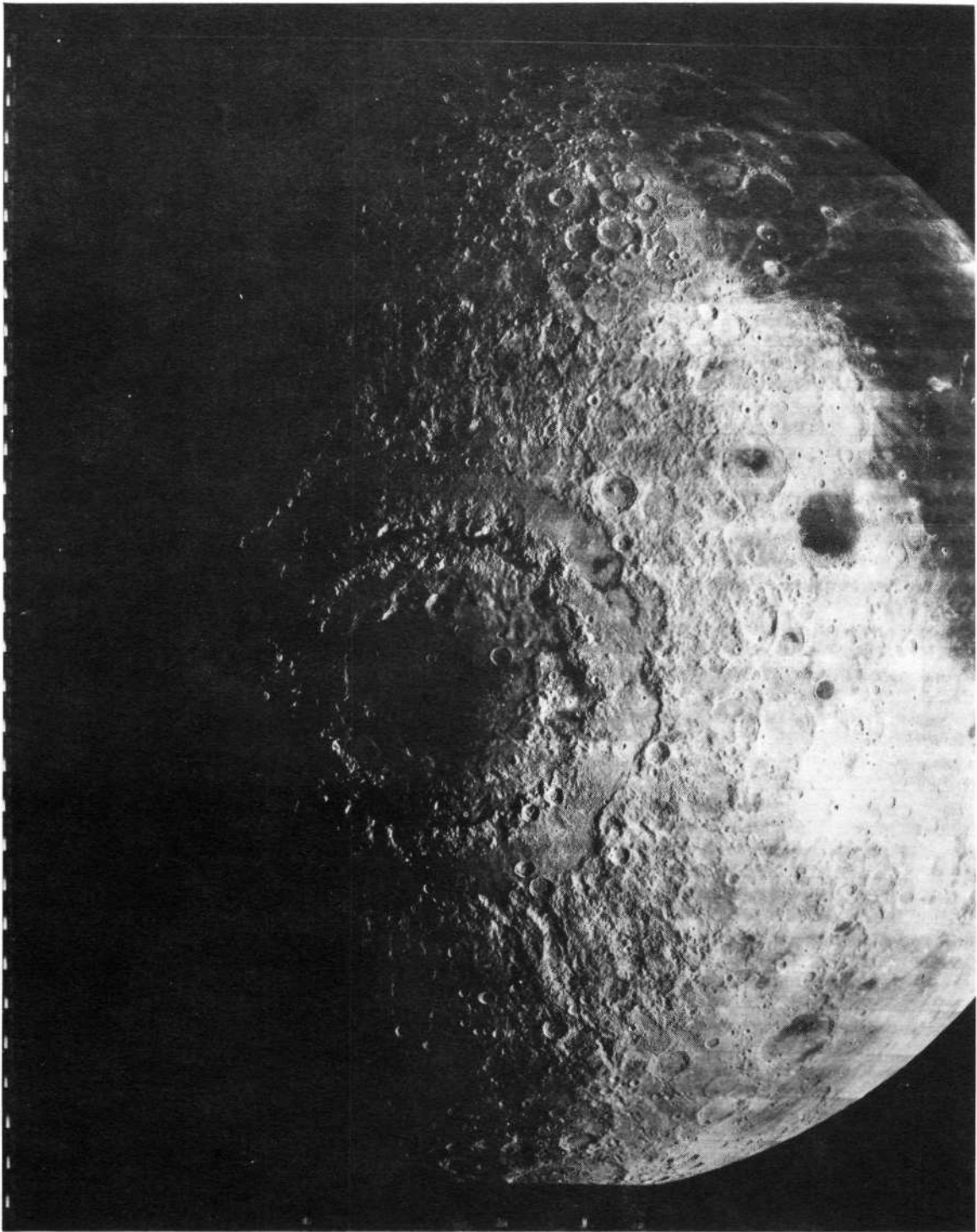


Figure 17. Orbiter 4 view of Mare Orientale, located on the limb of the moon and not entirely visible from Earth. The Orbiter picture shows Mare Orientale to be a large many-ringed basin about 600 mi across. Although Mare Orientale is one of the youngest basins on the moon, it contains very little dark mare material except for an apparently thin deposit in the center. NASA photograph IV-187-M.

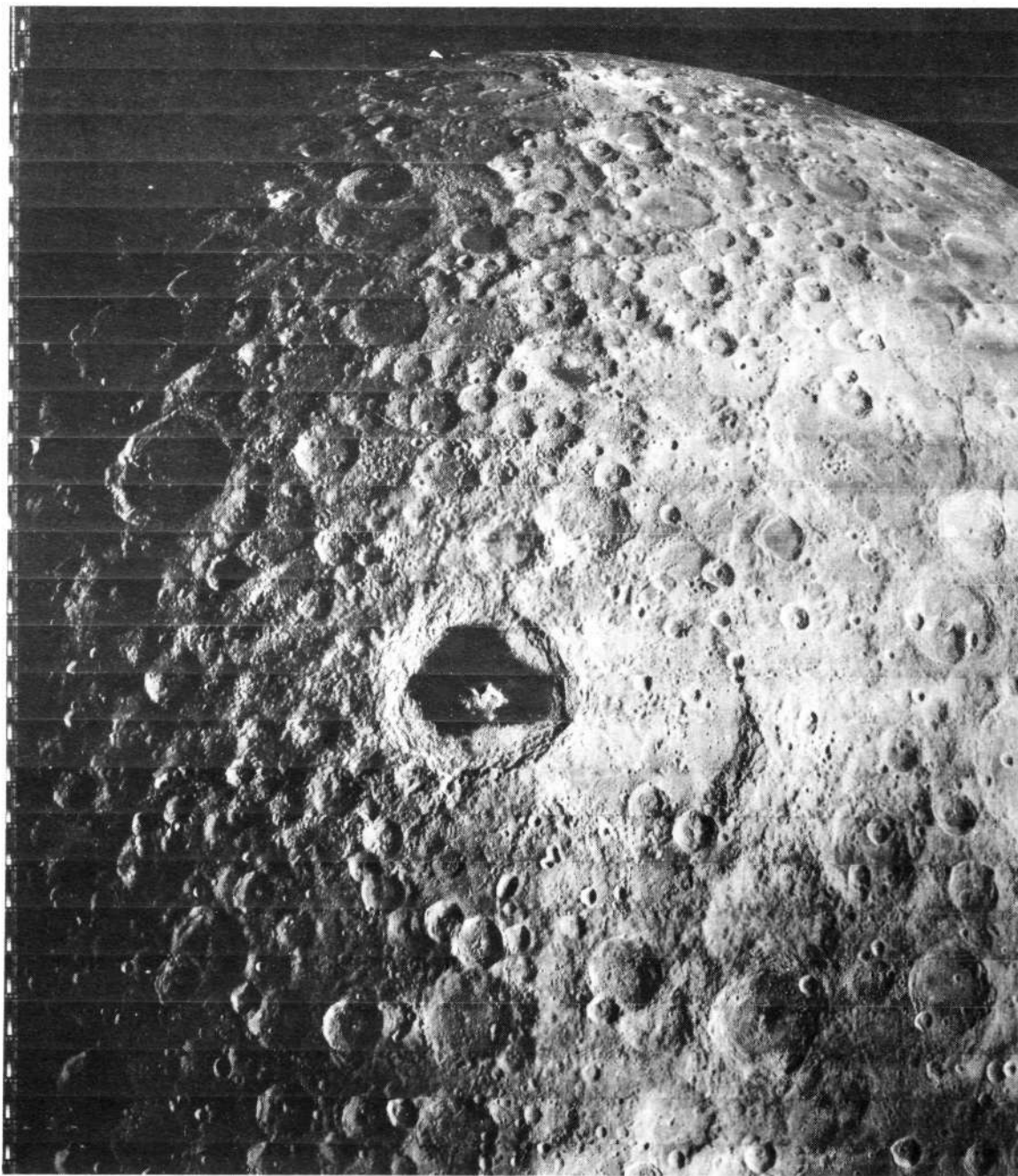


Figure 18. The crater Tsiolkovsky on the far side of the moon, photographed by Orbiter 3. The crater, which is about 150 mi in diameter, contains one of the few small areas of dark mare-like material observed on the back side of the moon. NASA photograph III-121-M.

time to send men, first to examine the surface from orbit and finally to land. The first goal was reached in 1968, when the crew of Apollo 8 went into orbit around the moon and became the first men in human history to watch their own home planet rise above the surface of another world (Figure 19). Two later Apollo flights checked out the complete Apollo system, Apollo 9 in earth orbit and Apollo 10 in lunar orbit. There was nothing left to be checked. And at last, on a sunny July afternoon, the Apollo spacecraft Eagle, piloted by Neil Armstrong and Edwin Aldrin, landed in Mare Tranquillitatis (Figure 20).

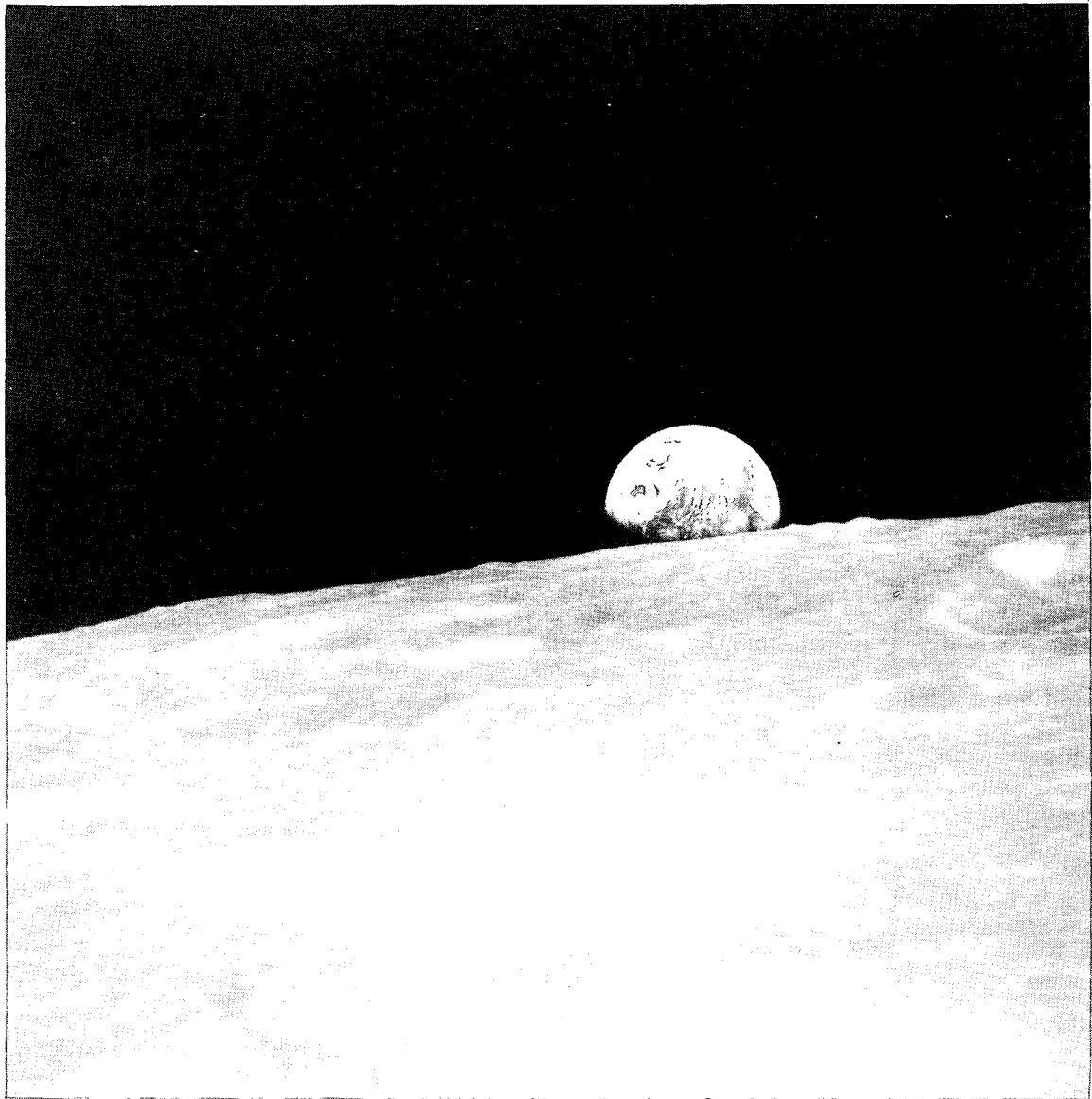


Figure 19. Apollo 8 photograph of an "earthrise" above the heavily cratered highland terrain of the moon. NASA photograph AS-8-2329.

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The landing of Apollo 11 was one of the few really great events in human history. Even now, from the perspective of three years, it is hardly possible to analyze it properly. For those of us who were present and participated in it, it meant many things. There was an element of national pride (Figure 21), overlain by a great feeling of human accomplishment and a gratitude at having been present. And from the point of view of the scientific exploration of the moon, a new era had begun. For the first time, man could walk on the moon, study it at first hand, return samples of its rocks and soil, and leave instruments behind to send back more data after him.

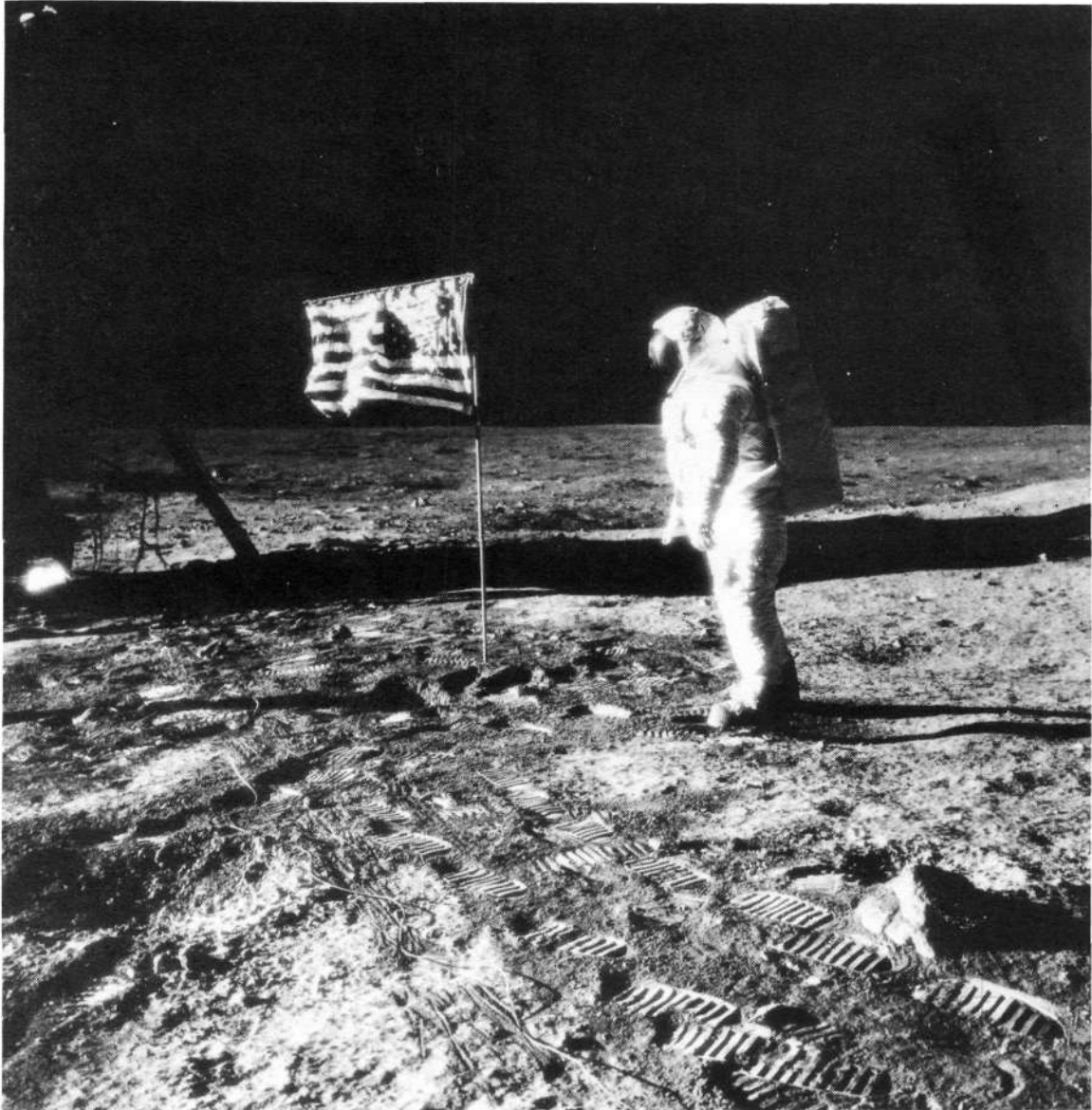


Figure 21. Astronaut Neil Armstrong by the American flag at Tranquillity Base, the Apollo 11 landing site. NASA photograph AS-11-5875.

The information sent back by the deployed instruments deserves a separate and detailed discussion of the insights that they have given us about the moon and its environment (see Appendix). The importance of being able to deploy instruments and experiments on the moon cannot be overstated. In Figure 22, Astronaut Aldrin is deploying an experiment to study the "solar wind," a stream of elemental particles that is continually ejected out of the sun and travels through the whole solar system. The apparatus, informally called "the windowshade," is a sheet of thin aluminum foil which can actually trap the solar particles in it. After the sheet has been exposed during the mission, it is returned to earth and the trapped particles are analyzed. In Figure 23, Aldrin is deploying two other instruments. One, a seismometer, measures the very weak "moon-quakes" that occur and thus gives us a look at the processes going on in the lunar interior. The other instrument, the Laser Ranging Retro-Reflector (called LR-cubed for short) is simply an intricate mirror which reflects back to earth a laser beam aimed at the moon. Using the laser beam, it is possible to measure the earth-moon distance at any time with a precision of about 15 cm (about six inches) in about 240,000 miles. Measuring this distance over periods of time, and using the additional reflectors left at later Apollo landing sites will provide an incredibly precise tool for measuring the behavior of the earth-moon system with time. The system may even be precise enough to use the lunar reflectors to measure the rate of sea-floor spreading and continental drift on earth.

The Apollo 15 mission was the fourth lunar landing, but for lunar science it was as unique in its own way as the Apollo 11 landing itself. Apollo 15 was the first of the so-called J-series of Apollo missions, which featured a great increase in lunar stay time, lunar surface mobility, scientific payloads, and sample return. In a scientific sense, Apollo 15 was a brand new start, and those who watched the performance of the crew on television as they moved around in the Lunar Rover and collected specimens from a wide area around Hadley Rille were witnesses to one of the most impressive scientific explorations in human history.

Figure 24 shows Apollo 15 Astronaut Jim Irwin with the Lunar Module (LM) and the Lunar Roving Vehicle (the "Rover"). Mount Hadley Delta rises about 11,000 feet high in the background. The Lunar Rover, which allowed the Apollo 15 crew to cover more ground than had been possible in the previous three Apollo missions combined, is shown in Figure 25 in front of Hadley Rille.

Another feature of the Apollo 15 mission was the extensive geological observations made by the crew on the lunar surface. Their discovery that the Apennine Mountains around the landing site show definite layering in them (Figure 26) was unexpected and is still the subject of considerable scientific discussion. In their exploration of Hadley Rille, the crew observed for the first

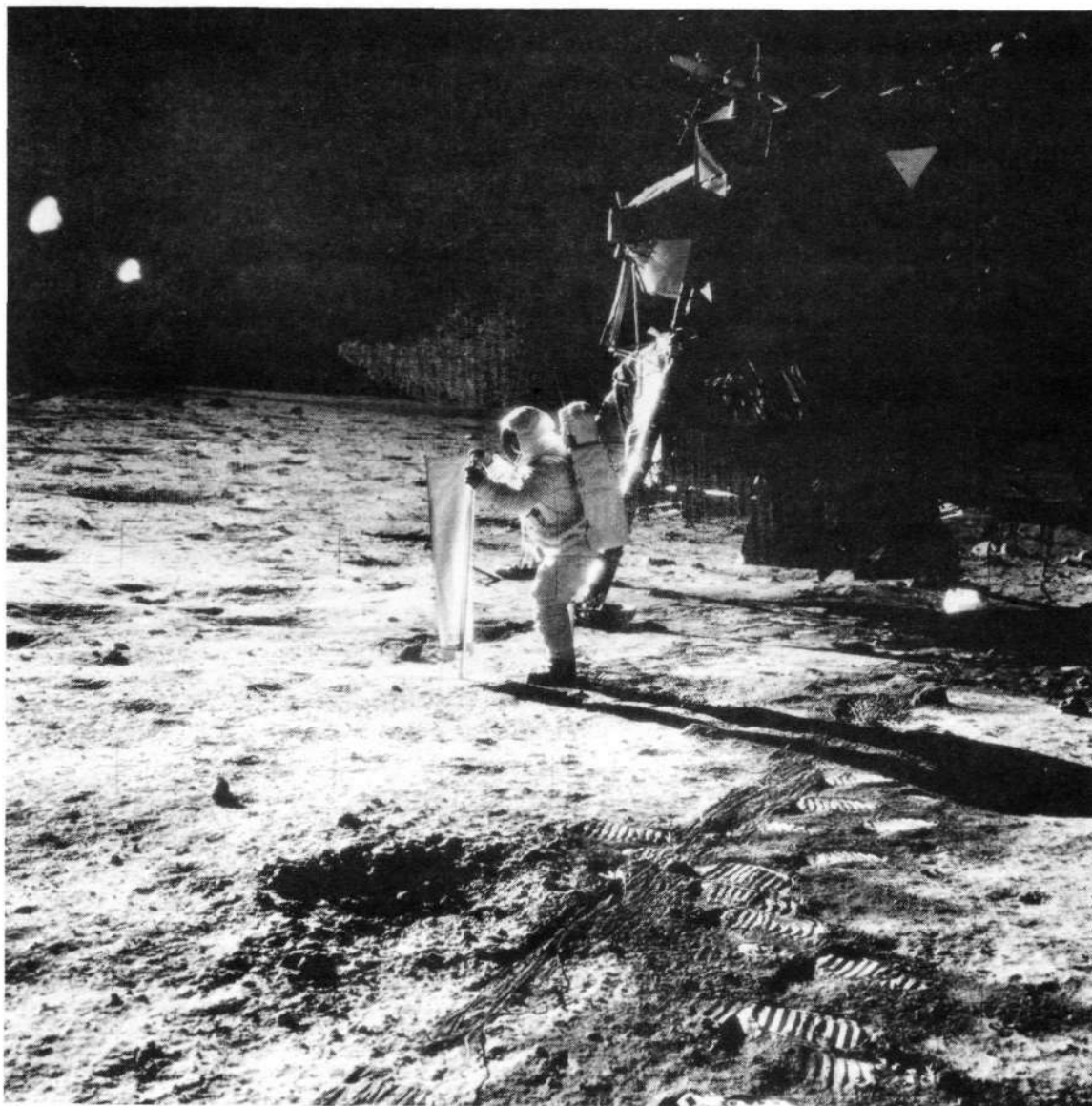


Figure 22. Astronaut Edwin Aldrin deploys the "windowshade," a sheet of aluminum foil designed to catch "solar wind" particles streaming out of the sun. The lunar module (LM) is in the background. NASA photograph AS-11-5872.

time actual lunar bedrock in place in the walls of the Rille. The bedrock exhibits very well-developed horizontal layers (Figure 27) strongly suggestive of the layered basalt flows that are thought to make up the maria at this point. At the Apollo 15 site, a number of large isolated boulders (Figure 28) could be sampled in detail.

The experiments done on the lunar surface during Apollo 15 included, for the first time, emplacement of an instrument to measure the amount of heat

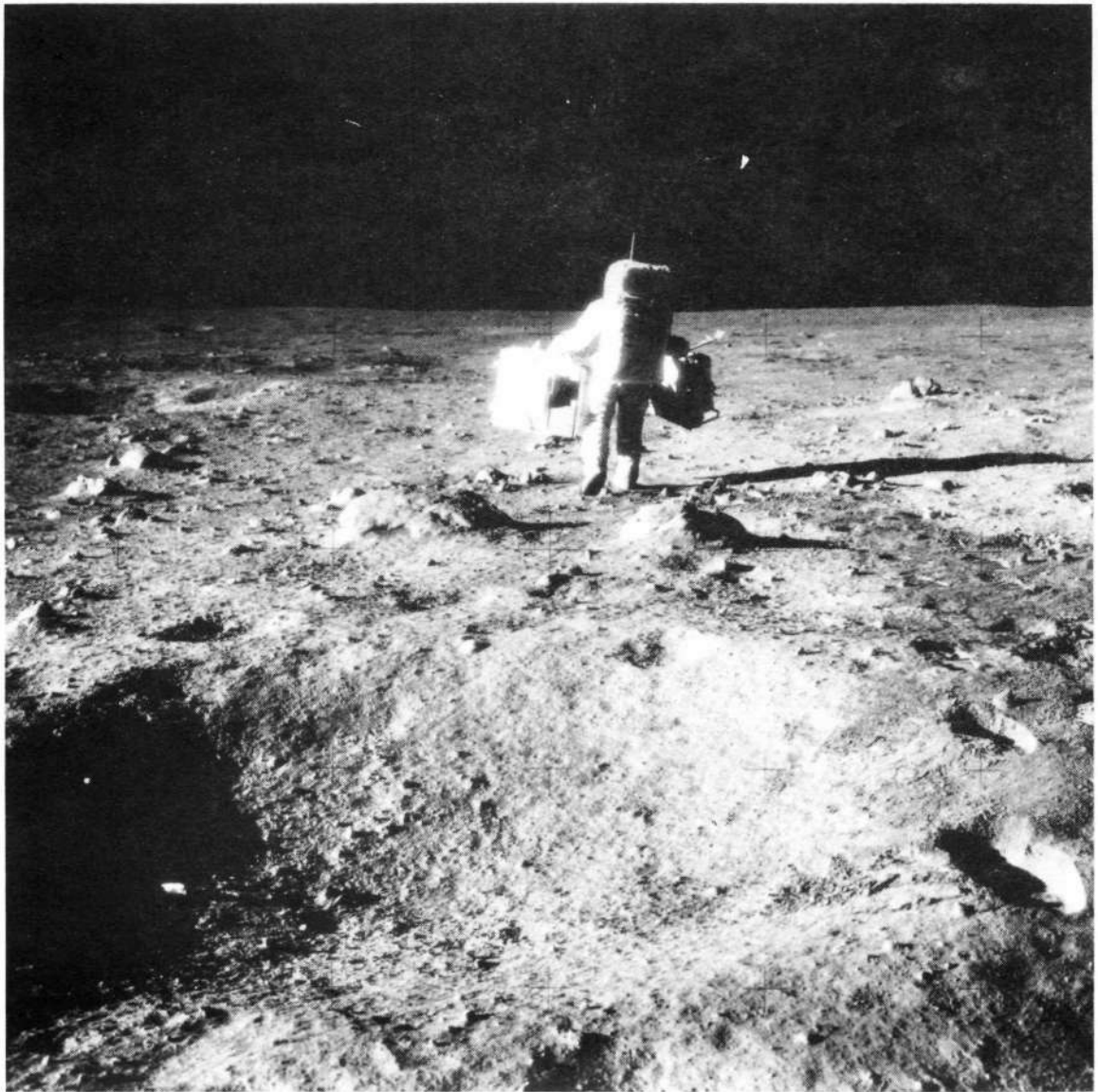


Figure 23. Apollo 11 Astronaut Edwin Aldrin deploys two geophysical instruments at Tranquillity Base. The instruments are a seismometer for measuring "moonquakes" and a laser beam reflector for measuring the earth-moon distance very precisely. NASA photograph AS-11-5944.

flowing out to the surface from the lunar interior. Surprisingly, the heat flow measured at Hadley Rille was many times higher than anyone had expected, nearly half that of the earth itself! Now scientists are waiting for the results of the Apollo 16 and Apollo 17 heat flow experiments to see if such high values are general for the whole moon. If they are, then a lot of present theories are going to have to be revised.



Figure 24. Apollo 15 Astronaut Jim Irwin salutes the flag at Hadley Rille, standing near the lunar module and the lunar rover (right). Mount Hadley Delta, in the background, rises about 11,000 feet above the landing site. NASA photograph AS-15-88-11866.

The science done on the lunar surface by Apollo 15 provided spectacular views, but the scientific experiments done in lunar orbit from the Command Module were equally outstanding. One of the most impressive experiments actually made chemical analyses of a large part of the lunar surface from orbit. This group of several experiments depended on the fact that, because the moon has no atmosphere, the X-rays emitted by the sun strike the lunar surface and generate other (secondary) X-rays from the atoms in the lunar rocks. These



Figure 25. Apollo 15 Astronaut Dave Scott with the lunar rover. Hadley Rille, in the background, is about 1,200 feet deep from rim to floor. Large boulders, probably eroded from the walls, are present in the bottom of the rille. NASA photograph 71-H-1426.

X-rays coming off the lunar surface are very weak, so weak that a thin metal foil or a few inches of air is enough to stop them (they are, of course, no danger to the astronauts). However, the instruments used are sensitive enough to analyze these X-rays, even from lunar orbit, and from these analyses the amounts of certain elements in the lunar rocks can be calculated.

Figure 29 shows one of the most important immediate results of this experiment. The instruments were able to measure the concentrations of aluminum (Al) and silicon (Si) in the lunar rocks, and the Al/Si ratio of these two elements is shown for different areas of the moon. One is struck immediately

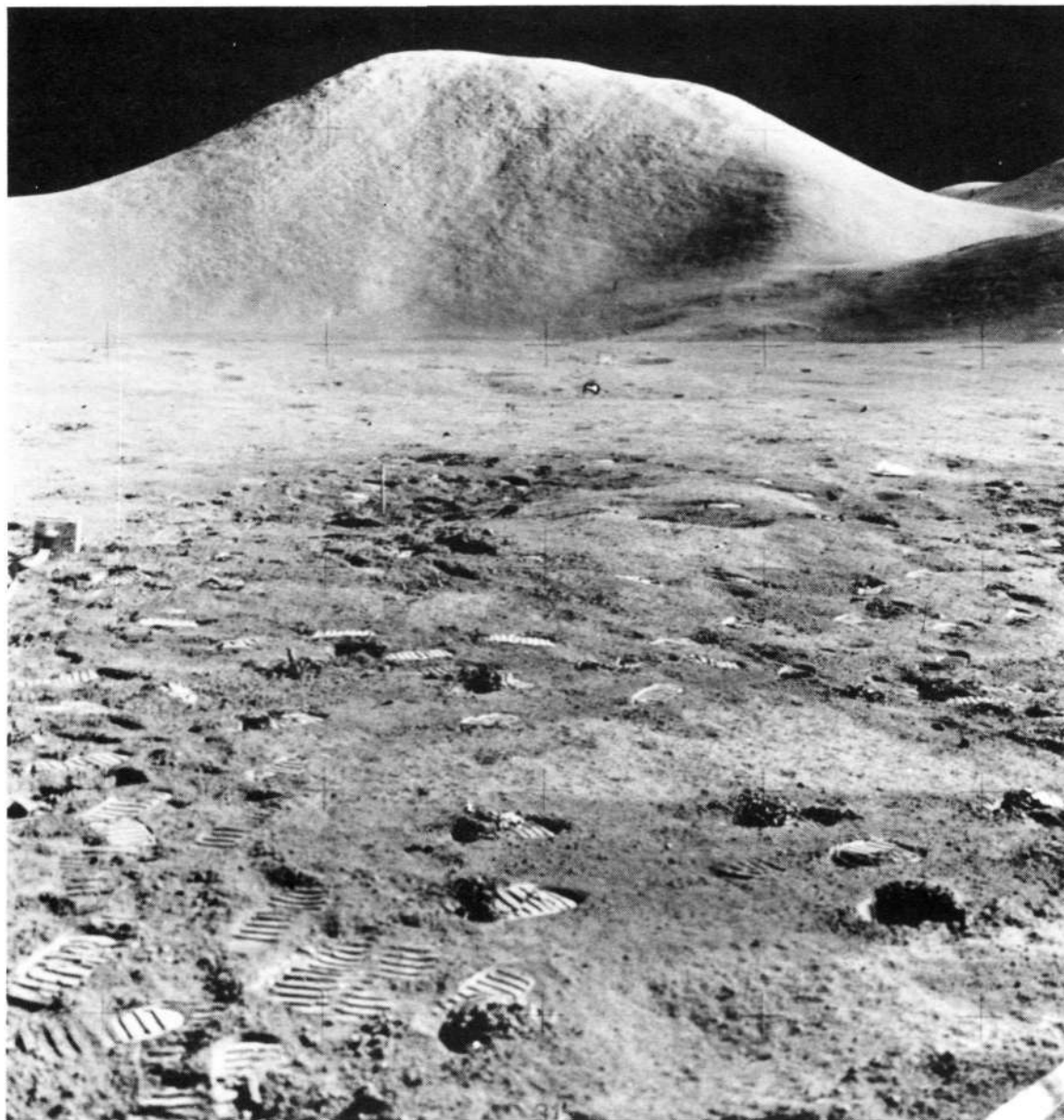


Figure 26. Mount Hadley, photographed from the Apollo 15 landing site near Hadley Rille. The mountain rises about 14,000 feet above the plain and shows unusual well-developed linear features which trend from upper right to lower left (light and dark alternations). The high-angle lineations may be produced by layering in the old pre-Imbrian deposits that make up the Apennine Mountains. Another, poorly-developed, set of lineations is nearly horizontal. NASA photograph AS-15-87-11849.



Figure 27. Telephoto view of the far rim of Hadley Rille, taken from near the Apollo 15 landing site. Note that bedrock is exposed in the wall (center of picture) and that the layer of soil (regolith) on top of the bedrock is very thin. The bedrock shows well-developed horizontal layers. The massive uppermost layer is about 80 feet thick, while the layers beneath it are only a few feet thick. The subdued crater on the maria surface beyond the rille (upper left) is about 400 feet in diameter. NASA photograph AS-15-89-12157.



Figure 28. Large boulders exposed on the rim of Dune Crater near the Apollo 15 landing site. The largest boulder displays very large cavities several inches across, while the smaller boulder in the background shows well-developed, steeply inclined, layering. Both boulders are coarsely crystalline basalts apparently derived from the mare surface. NASA photograph AS-15-87-11778.

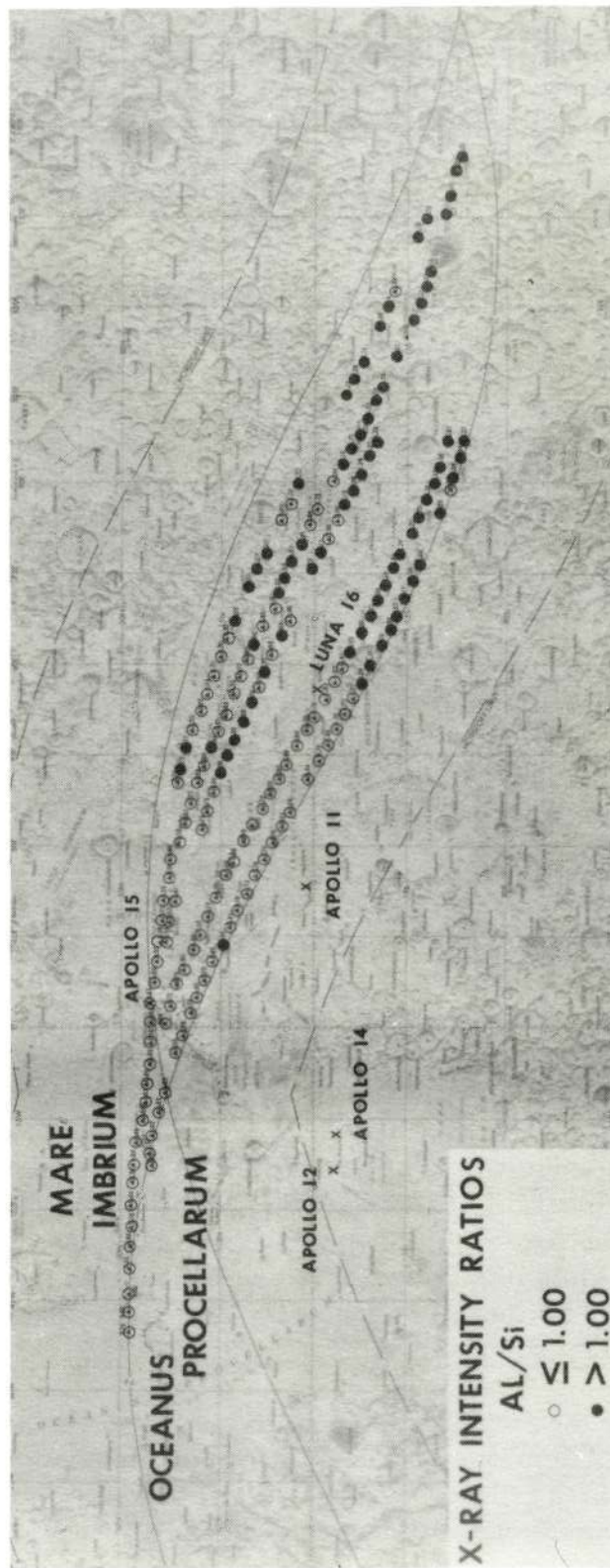


Figure 29. Map of the lunar surface, showing the paths taken by the Apollo 15 command module in lunar orbit and the results of analyses of lunar surface composition by the Orbital Science Experiment. Each circle represents the Al/Si ratio determined by analyzing X-rays emitted by the lunar surface. Note that low Al/Si ratios (open circles) are predominantly located in areas of maria (left side), while higher Al/Si ratios are found in highland areas (right side). These results indicate that the maria and highlands are distinctly different in chemical composition, with the highland areas being enriched in Al. Data courtesy of I. Adler.

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by the fact that the low Al/Si ratios (open circles) are all clustered in the areas of lunar maria, while the higher Al/Si ratios (dark circles) occur in the highland areas. Figure 30 shows the same data as a graph; again, the mare areas have lower values and form "valleys" on the graph, while the "peaks" of higher Al/Si ratios are found in the highland areas. Because all lunar rocks studied have about the same amount of silicon, this result indicates that the highland areas are richer in aluminum than are the maria.

This orbital experiment was therefore an impressive confirmation of some of the theories suggested after the Apollo 11 and Apollo 12 samples had been studied; namely, that the color division of the moon into dark maria and lighter highlands is a result of a real chemical difference involving actual separation of different elements. Furthermore, this chemical separation, or differentiation, must have taken place very early in the moon's history, because we now know from dates on returned lunar samples that the highland rocks must be at least 4.0 billion years old or older, very close to the figure of 4.6 billion years calculated for the age of the solar system itself.

ORIGIN OF THE RETURNED LUNAR LAVAS

Without any doubt, the most important scientific result of the manned lunar landings was the return of lunar rock and soil samples for scientists to work on in their own laboratories. The rocks may not have looked too impressive when first seen, coated with lunar dust, when the sample containers were opened at the Lunar Receiving Laboratory (Figure 31), but their return to earth was the greatest breakthrough in lunar studies since the invention of the telescope.

The samples from Apollo 11 and from later Apollo missions have been studied in detail by over 1000 scientists, both American and foreign, using every analytical method known to man. The amount of data produced by these studies is incredible; the papers presented at the three Lunar Science Conferences held so far fill nine 800-page volumes, and there have also been numerous additional articles in professional journals. In this section, I will review the chief results obtained from study of the Apollo 11 and Apollo 12 samples, concentrating on the methods which geologists like myself have used to analyze the rocks and to derive conclusions about how they were formed. The major conclusions from these studies can be briefly summarized:

1. The rocks from the maria sites sampled by Apollo 11 and Apollo 12 are igneous, which means that they formed by the cooling and crystallization of a molten silicate liquid, much like volcanic rocks erupted on earth in areas like Hawaii, Iceland, and Oregon. This fact, which

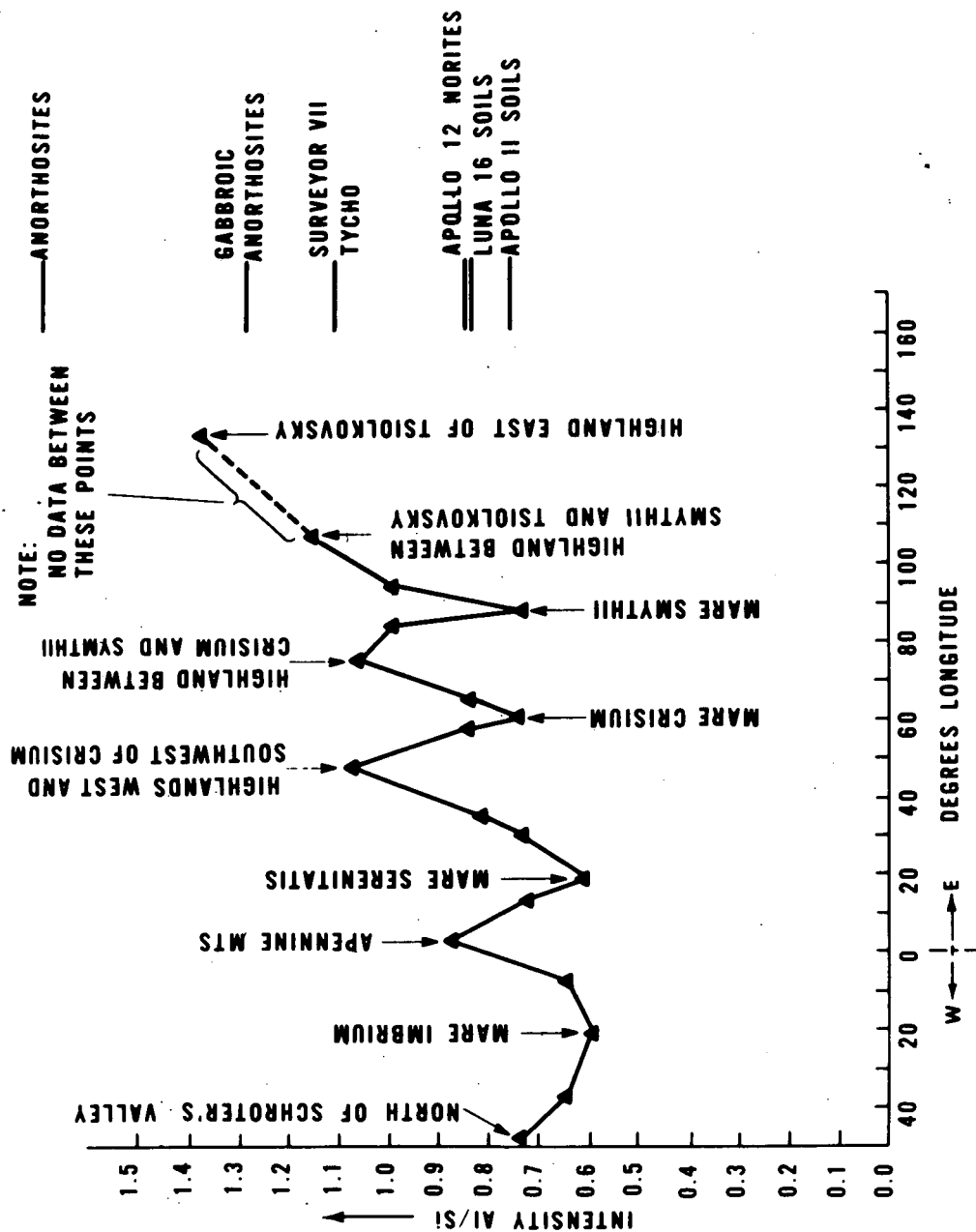


Figure 30. A plot of Al/Si intensity, determined by the Apollo 15 Orbital Science Experiment, as a function of lunar location. Mare areas have consistently lower values than do highland areas. The Al/Si ratios determined for several lunar samples are shown at the right. Note that the higher Al/Si ratios in the highlands are like those of feldspar-rich rocks such as gabbroic anorthosite, but the ratios are not high enough for anorthosite (a rock composed entirely of feldspar). These results show that the lunar highlands cannot be made entirely of anorthosite. Data courtesy of I. Adler.

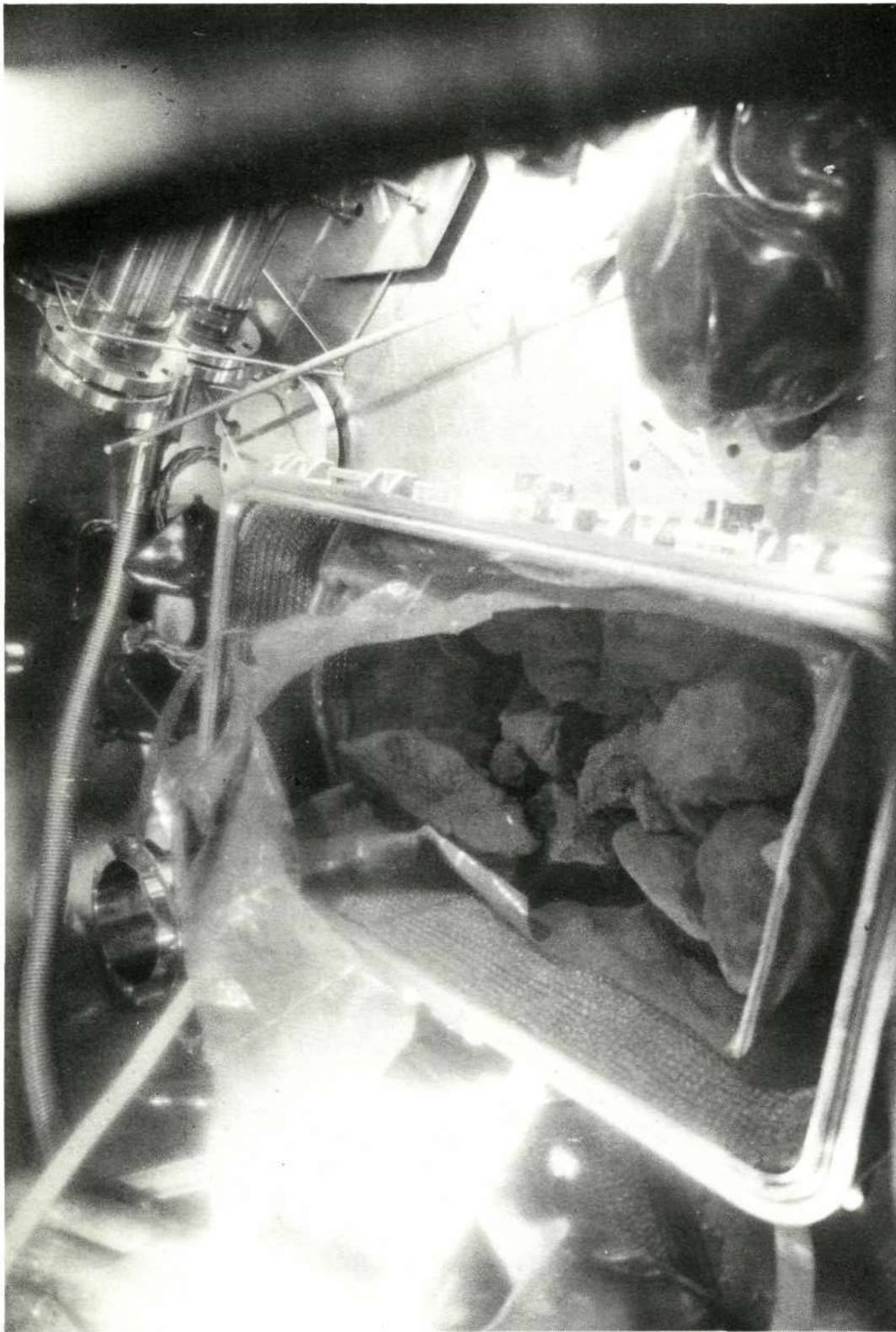


Figure 31. Dust-coated Apollo 11 samples in the sample container when the container was first opened at the Lunar Receiving Laboratory. NASA photograph S-69-45002.

was recognized immediately when the Apollo 11 rocks were examined, is one of the most important pieces of data obtained by the Apollo landings. The existence of such rocks on the moon implies that, at some time in the past, the moon was hot enough inside to melt part of its interior and to pour the molten rock out onto its surface. Thus, the Apollo 11 samples destroyed, very quickly, the theory that the moon had always been a cold dead body since its formation. At the same time, the lava samples raised new questions about how hot it had gotten or how rapidly it had cooled off since the lavas were formed.

2. The maria samples have the same general characteristics as some terrestrial volcanic rocks (basalts). However, they show real differences as well, and lunar and terrestrial basalts can be easily distinguished. The maria basalts are richer in iron than are terrestrial basalts, and they are also very depleted in volatile elements like potassium and sodium. The lunar basalts have formed under very oxygen-poor conditions (reducing conditions), and they contain virtually no water.
3. The maria samples are unusually old. The Apollo 11 rocks were apparently formed about 3.7 billion years ago, while the Apollo 12 rocks are slightly younger, dated at 3.3 billion years. These rocks are therefore older than almost any preserved terrestrial rocks. Furthermore, because the maria are the youngest features on the lunar surface, these ages indicate that most of the lunar surface and the highland areas are even older and may possibly date back to the formation of the moon, which we believe took place about 4.6 billion years ago.
4. The lunar samples contain no life forms and only trace amounts of detectable carbon and organic compounds. This result has been so definite that much of the excitement about the biological possibilities of lunar exploration has subsided. During preliminary analyses of the Apollo 14 samples, no analyses for organic compounds were even made, and the Apollo 15 crew was able to omit the quarantine period which had been set up for the earlier missions to prevent possible contamination.

One of the Apollo 11 samples, cleaned off, is shown in Figure 32. It is a massive rock composed of very small mineral crystals and containing large bubble cavities (vesicles) which were probably formed by escaping gas at the time the rock solidified. Figure 33 compares the chemistry of the lunar rocks with a terrestrial basaltic rock, and the chemical differences between the two types of rock are really obvious. The lunar basalt has a higher TiO_2 content, higher FeO , no oxidized iron (Fe_2O_3), much lower alkalis (Na_2O and K_2O) and virtually no water.

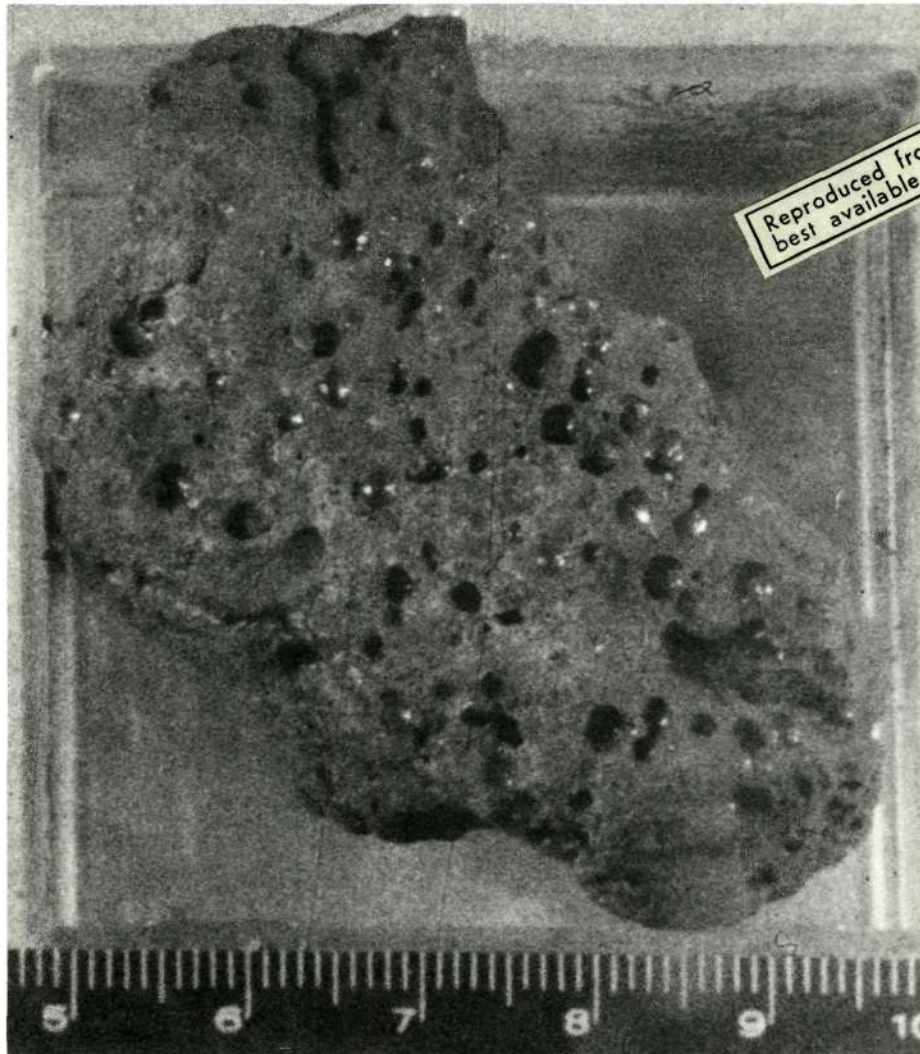


Figure 32. A fine-grained crystalline Apollo 11 basaltic rock. The large circular areas which reflect the light are bubbles (vesicles) formed by escaping gas as the molten rock was cooling. NASA photograph S-69-45209.

Although the chemistry of the lunar and terrestrial rocks is significantly different, most of the minerals are quite similar. The minerals that make up the bulk of the lunar rocks (Figure 34) are the same as those found in terrestrial basalts. The lunar rocks are made up chiefly of: (1) pyroxene, a Ca-Mg-Fe silicate mineral; (2) feldspar, a Ca-Al-silicate; and (3) ilmenite, an opaque Fe-Ti-oxide. The fact that native iron occurs in small amounts in the lunar rocks distinguishes them from terrestrial basalts and shows the reduced conditions under which they have formed.

The next few figures show what these rocks look like under the microscope. For microscopic study, the lunar samples are made into what geologists call

TERRESTRIAL ROCK		APOLLO 11	
		ROCK	DUST
SiO_2	48.01	42.01	41.50
TiO_2	2.92	8.81	7.50
Al_2O_3	15.97	11.67	14.31
Fe_2O_3	3.87	0.00	0.06
FeO	7.56	17.98	15.62
MgO	5.26	6.25	7.95
CaO	9.04	12.18	11.84
Na_2O	3.73	0.48	0.48
K_2O	1.89	0.11	0.16
H_2O^+	1.33	0.00	0.00
P_2O_5	0.42	0.08	0.10

Figure 33. Table showing chemical comparisons between a terrestrial basaltic rock and Apollo 11 rock and soil. Note that the Apollo 11 sample has much higher TiO_2 and FeO than does the terrestrial one. However, the Apollo 11 samples have very low alkalis (Na_2O and K_2O), while Fe_2O_3 and water are entirely absent.

"thin sections." These sections are made by placing a slice of the sample on a glass slide and grinding and polishing it very thin, down to about 0.03 millimeters, just as a doctor might prepare a tissue section for study. When the rock is polished this thin, one can shine polarized light through it and use the color and optical properties of the minerals to identify them. The methods are essentially those that geologists have been using for over 100 years to examine rocks, but the results they yield are quite spectacular.

MINERALS FOUND IN THE LUNAR SAMPLE

<u>MINERAL</u>	<u>COMPOSITION</u>
PYROXENE	(Ca, Mg, Fe) SiO ₃
FELDSPAR	Na Al Si ₃ O ₈ – CaAl ₂ Si ₂ O ₈
ILMENITE	Fe Ti O ₃ (– Fe ₂ O ₃)
TROILITE	Fe S
IRON	Fe
APATITE	Ca ₅ (PO ₄) ₃ (F, Cl, OH)

Figure 34. Compositions of minerals found in the Apollo 11 basaltic rocks. The minerals are the same as found in most terrestrial basalts. The major minerals in both terrestrial and lunar basalts are pyroxene, feldspar, and ilmenite. The other minerals occur only in small amounts.

These microscopic thin sections have an added advantage. One can use them in an instrument called the electron microprobe to obtain chemical analyses of the minerals without destroying them. This instrument shoots a thin beam of electrons at the sample, just like the picture tube in a television set. When the electrons hit the atoms that make up the sample, these atoms give off X-rays, much in the same way that X-rays can be given off by a badly shielded television tube. Each element gives off its own characteristic X-ray, like a fingerprint, and most of the equipment of the electron microprobe consists of detectors to identify these X-rays and to measure their intensity.

Using this instrument, one can obtain analyses from spots a few thousandths of a millimeter in diameter without destroying the samples at all. One can thus make hundreds of analyses from a single grain or a single rock specimen. Almost all of the chemical analyses of lunar material have been made in this way. Indeed, if it had not been for the electron microprobe, this vast amount of data could never have been obtained, because other methods of chemical analysis use up too much material to be used to any great extent on lunar samples.

Under the microscope (Figure 35) the typical lunar basalt is composed of crystals of gray pyroxene, white or clear feldspar, and black opaque ilmenite. In another specimen (Figure 36) the same minerals are found. In both specimens, the crystals are all about the same size, and they are intergrown with each other in a typical texture produced by rapid cooling, implying that this rock was solidified quickly at or near the lunar surface.

In polarized light (Figure 37), the crystals act like polaroid prisms, and their colors give indications about their optical properties. The feldspar has a light grayish color, while the associated pyroxene has darker, more intense colors which serve to identify it.

The colors of the minerals in polarized light are not only useful for identifying the minerals themselves, but they also give information about the chemical composition of each grain. Figure 38 shows a grain of pyroxene from an Apollo 12 sample which is chemically zoned; that is, the chemical composition is different in the different parts of the grain. The lighter inner part (which is yellow in color) is low in Ca and high in Mg, while the outer rim (red-purple in color) is higher in Ca and in Fe. If one makes a traverse across the grain with the electron microprobe, analyzing points in both the core and rim, one can follow in detail the chemical variations indicated by the colors. This zoning indicates that the first part of the crystal to grow, the inner core, formed from a liquid that was low in Ca and Fe, and that, as the crystal grew, the composition of the liquid changed so that the outer parts of the crystal were enriched in Ca and Fe. Thus, the study of one single crystal becomes the key to recognizing the chemical changes that took place in the silicate melt while the crystal was growing.



Figure 35. Photograph of a thin section of an Apollo 11 basaltic rock, examined under the microscope in transmitted light. The basalt is composed mainly of three minerals: pyroxene (gray crystals with fracture lines), feldspar (white lath-shaped crystals), and ilmenite (black opaque crystals). Sample 10047; long dimension of photograph is about 4 mm. NASA photograph S-69-47907.

A unique characteristic of the lunar basalts is that virtually all the iron is in the Fe^{2+} (reduced) chemical state rather than in the Fe^{3+} (oxidized) state as is the case in terrestrial volcanic rocks. These conditions have caused the formation of several new minerals that are found in minor amounts in the lunar rocks. Figure 39 shows the first of these minerals to be recognized, a silicate mineral like pyroxene but containing only Ca and Fe^{2+} , and called pyroxferroite. In this figure, the pyroxferroite forms darker yellow rims around a lighter crystal of pyroxene. This mineral has never been observed on earth and could only have formed in the unusual chemical environment of the lunar basalts.

The pyroxene crystals in the lunar rocks show other features that give us clues as to how the rocks formed. Figure 40 is a very high-magnification view of a single pyroxene crystal, and you can see numerous parallel lines that are produced by very thin planes or layers within the crystal. These planes, which are called exsolution lamellae, form because the single pyroxene crystal, as it cools from its original high temperature (about 1150°C), tends to separate into two different kinds of pyroxene which are stable at lower temperatures. Given enough time, this single crystal would have separated, or exsolved, entirely into two separate crystals of different composition. As you can see, the lamellae are very thin, only a few thousandths of a millimeter across. This tells us that the rock cooled from its initial temperature very rapidly, so that the crystal did not have time to separate and become "frozen" before separation had produced more than the very thin planes you see here. This kind of evidence tells us that the lunar rocks were cooled, or quenched, very rapidly, indicating that they solidified on or near the lunar surface, where the heat loss was rapid. They were probably formed as thin, rapidly-cooled flows rather than as thick, slowly-cooling bodies.

The lunar rocks, which formed from a complicated mixture of elements in a silicate melt, did not solidify all at once, the way a pure substance like water freezes instantaneously at a specific temperature. The lunar rocks probably started to crystallize at about 1150°C – 1200°C , but they were not completely solid until about 800°C – 900°C . As they solidified, the first minerals to form, such as pyroxenes and feldspar, were richer in the elements Ca, Mg, and Al than was the liquid, and as the crystals grew these elements were removed from the melt. As a result, the more the rock crystallized, the more the composition of the remaining liquid differed from that of the original melt. The effect was something like that observed when one freezes something like beer or antifreeze; the water tends to freeze out first, leaving the remaining liquid increasingly enriched in alcohol.

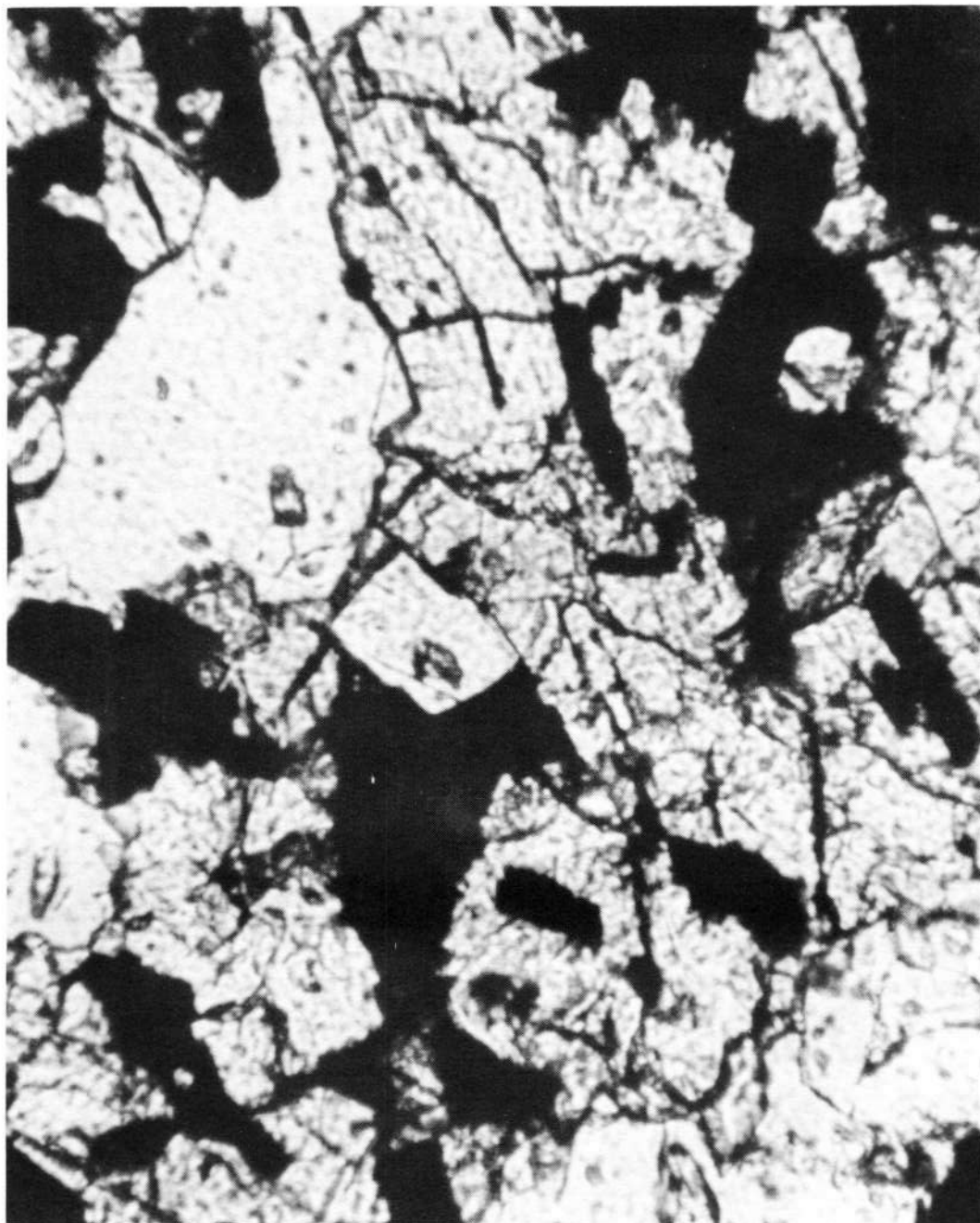


Figure 36. Photomicrograph of a fine-grained Apollo 11 basalt composed of the same three minerals as the specimen in Figure 35: pyroxene (gray, center) feldspar (white, top right), and ilmenite (black). Specimen 10017; long dimension of photograph is about 0.1 mm. Photograph courtesy of L. S. Walter.

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Figure 37. Same view as in Figure 36, but seen in polarized light. The feldspar shows gray colors and bands, while the pyroxene shows red and blue colors that appear as medium gray. The opaque ilmenite does not transmit light and is black. Photograph courtesy of L. S. Walter.

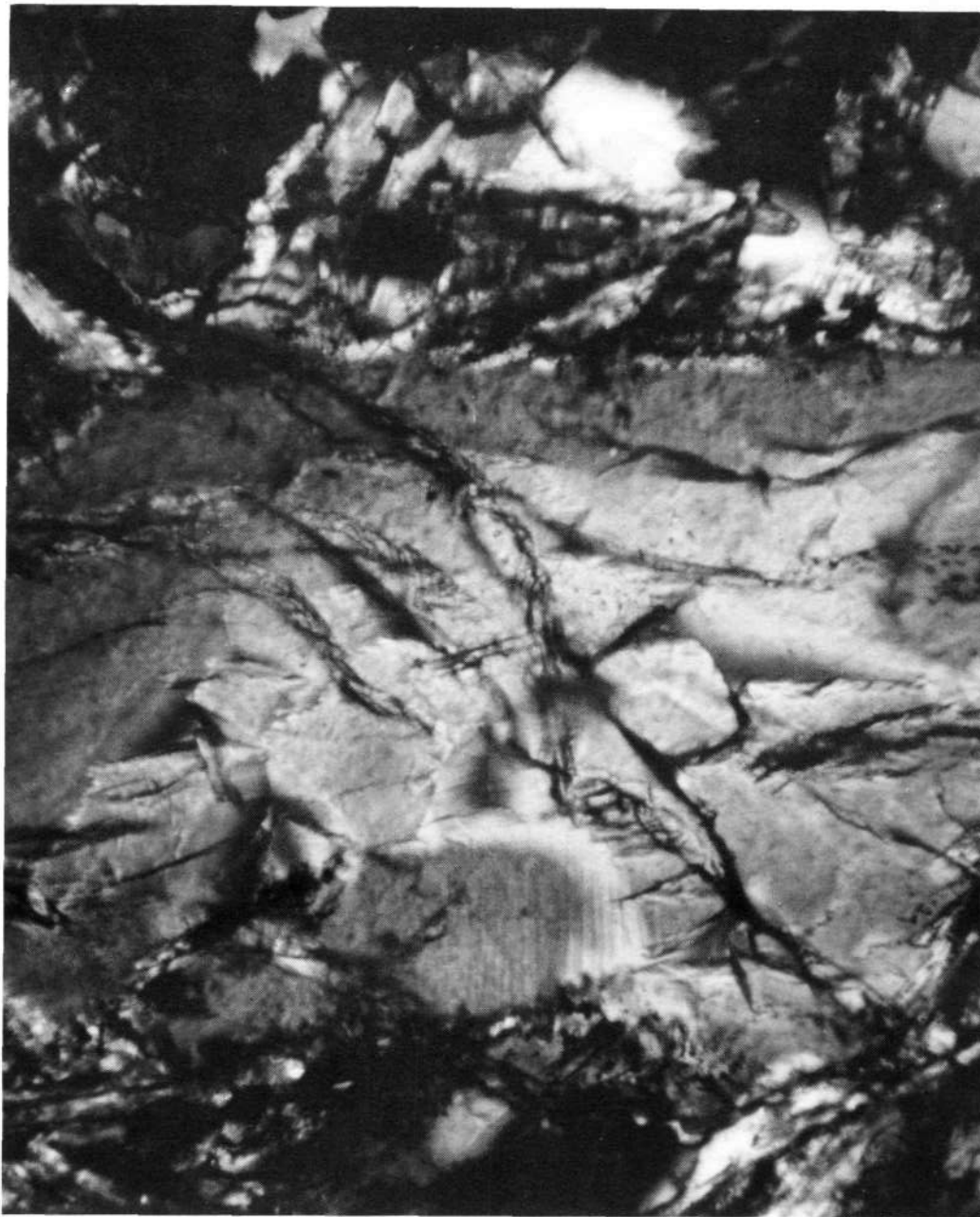


Figure 38. Large crystal of pyroxene in an Apollo 12 sample, seen in polarized light. The crystal shows different colors in its center and rim which indicate differences in chemical composition. The center is yellow (Mg-rich, Ca-poor), while the rim is red to purple (Ca-rich, Mg-poor, and Fe-rich). Note the fine horizontal lines (exsolution lamellae; see Figure 40) at the left side of the crystal. Sample 12004; long dimension of photograph is about 4mm. Photograph courtesy of L. S. Walter (see also Frontispiece).

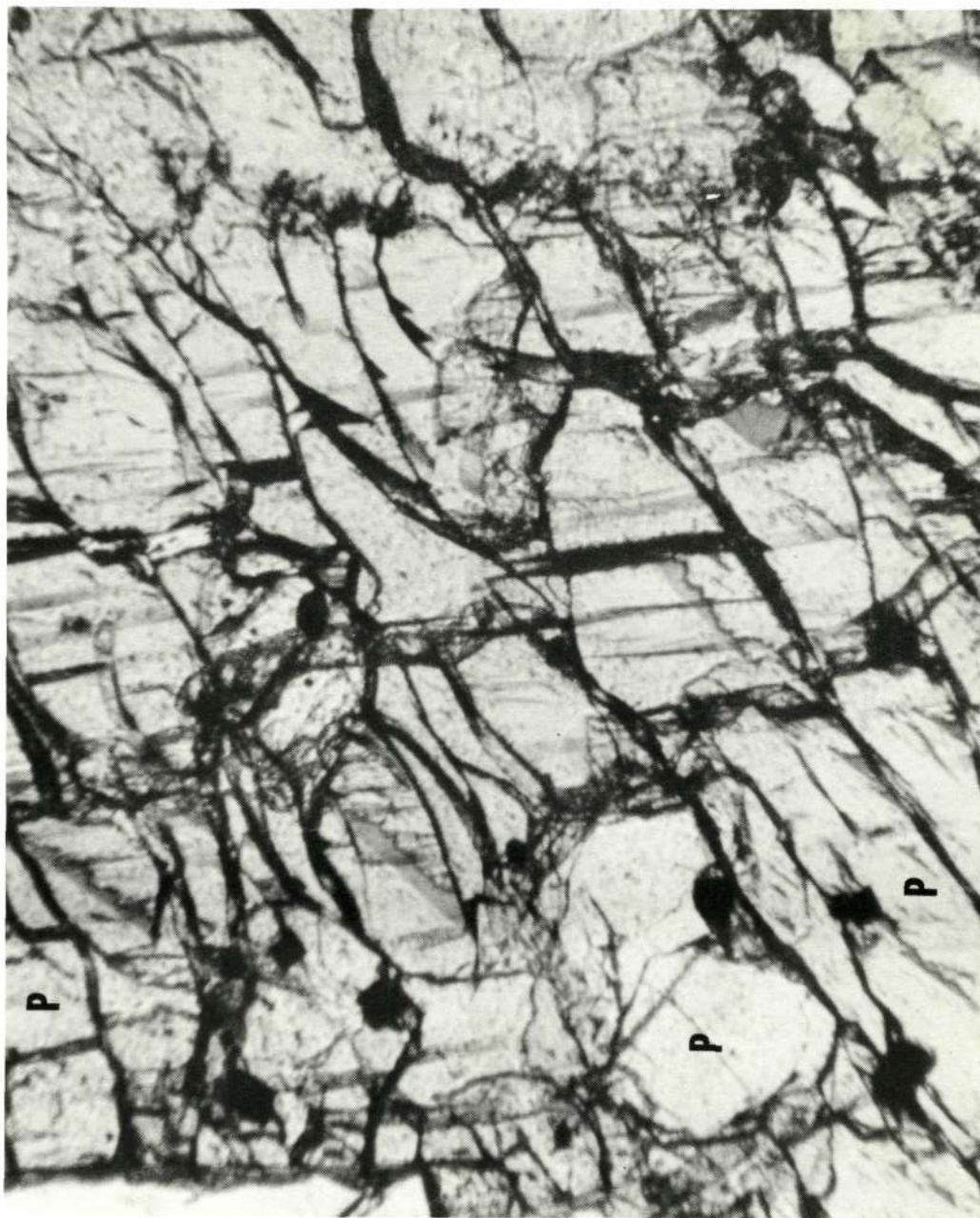


Figure 39. Crystals of a new mineral, found only in lunar samples, and called pyroxferroite. The yellow crystals (shown by letters "p") are growing around the edge of a large brownish pyroxene crystal (center of picture). Note that the pyroxene crystal has a well-developed set of parallel fractures (cleavage), while fracturing in the pyroxferroite crystals is much more irregular. Sample 12040; long dimension of photograph is about 1 mm. Photograph courtesy of L. S. Walter.

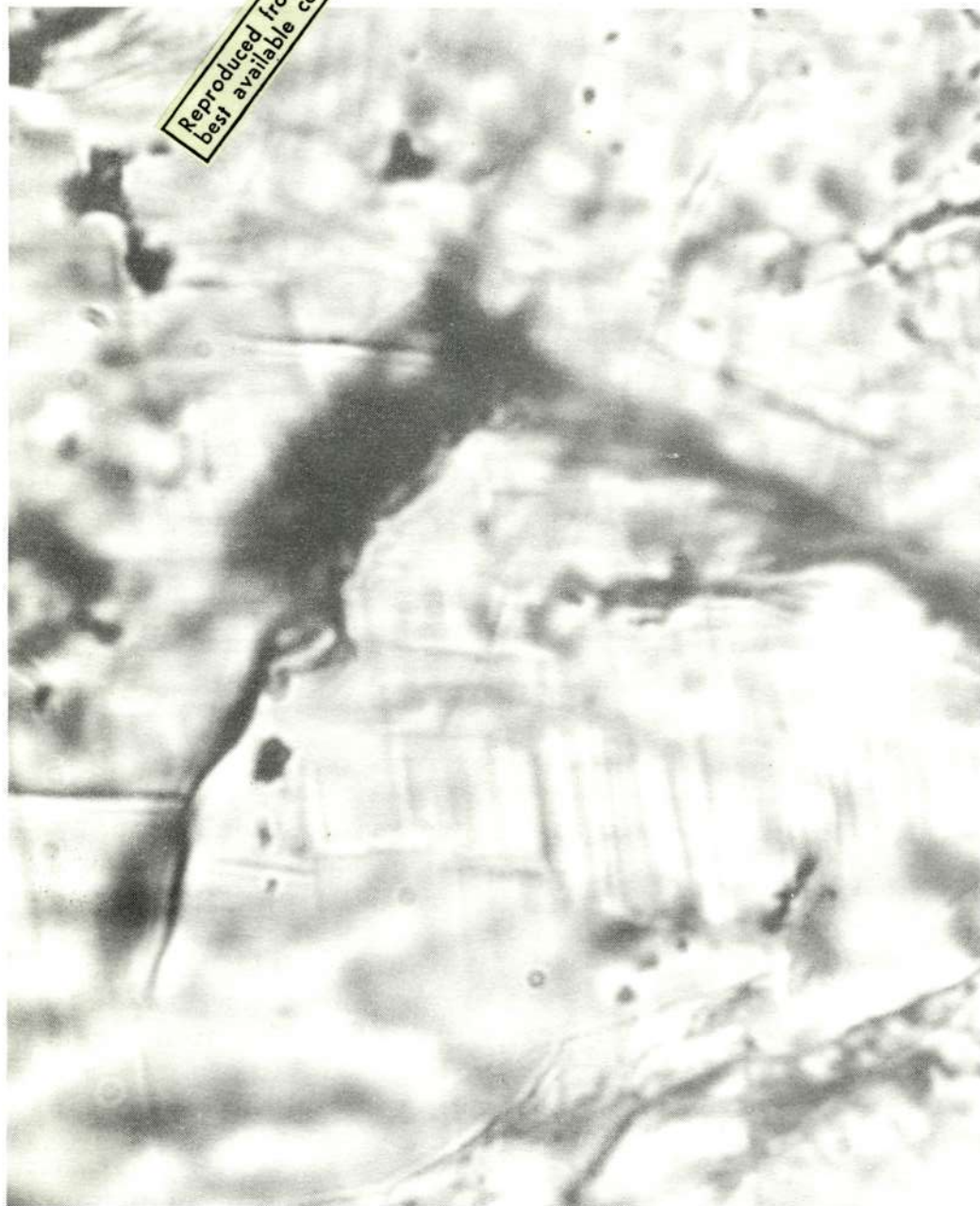


Figure 40. Very fine parallel lines, less than 0.01 mm thick, in a crystal of lunar pyroxene. The lines (called exsolution lamellae) are produced by the partial separation during cooling of the single pyroxene crystal into crystals of two different kinds of pyroxene. The fact that the lines are so thin shows that the crystal cooled very rapidly before much separation could take place. Sample 12018; long dimension of photograph is about 0.2 mm. Photograph courtesy of L. S. Walter.

This process, which is called fractional crystallization, is commonly observed in terrestrial igneous rocks. In the lunar samples this fractional crystallization produced residual liquids that were highly enriched in elements such as Si, K, Fe, and P. The result was formation of an unusual residual liquid or mesostasis which solidified in cracks between the earlier crystals and makes up about 1-5 per cent of the samples. A photograph of one of these areas is shown in Figure 41. The clear area with the distinctive "crackle" texture is a mineral called cristobalite, which is composed of pure SiO_2 , while the dark area is composed of glass and crystals of unusual minerals which are very rich in K, P, and Fe. The original melt from which the Apollo rocks crystallized contained about 45 per cent SiO_2 , and this shows how effective this fractional crystallization process is in separating different elements, because it leads eventually to the formation of a mineral composed of 100 per cent SiO_2 .

Because the cooling of the lunar rocks was quite rapid, the growing crystals occasionally trapped small drops of liquid within them as they grew. These pockets of trapped liquid then crystallized independently of the rest of the rock and now remain to give us a clue of what the original liquids were like while the crystals were forming. Figure 42 shows a very small inclusion of such liquid in a larger silicate crystal. The inclusion is about 1/20 of a millimeter long and is now composed of glass and very tiny crystals. On a larger scale, Figure 43 shows a large clear plagioclase feldspar crystal about four millimeters long. The central area within the crystal was apparently a large drop of liquid trapped by the growing crystal. This drop then cooled to form several different minerals within the plagioclase grain, including the gray pyroxene, the black ilmenite grain, and the clear areas of pure SiO_2 .

The extremely reducing conditions of low oxygen pressure are best indicated by the opaque minerals (oxides and sulfides) in the lunar samples. Because these minerals are opaque, they cannot be studied by shining light through them. They can, however, be examined by reflecting light off the highly polished surface of the grains, and in this way their identity and structure can be recognized. Figure 44 shows small inclusions of native iron metal, which is almost never found in terrestrial basalts. The iron occurs as small bright inclusions in larger grains of troilite (iron sulfide), and it is believed that these iron-troilite grains formed by solidification of sulfide melt droplets at the same time that the parent silicate melt was crystallizing. Another opaque mineral observed in the lunar rocks, chrome-spinel, is shown in Figure 45. The large grain of chrome-spinel has, during cooling, crystallized out or exsolved smaller blades of lighter-gray ilmenite. The compositions of the two minerals together can be used to estimate the temperature and oxygen pressure at which they formed. It is from observations like these that the formation temperatures and the highly reduced states of the lunar lavas can be determined.

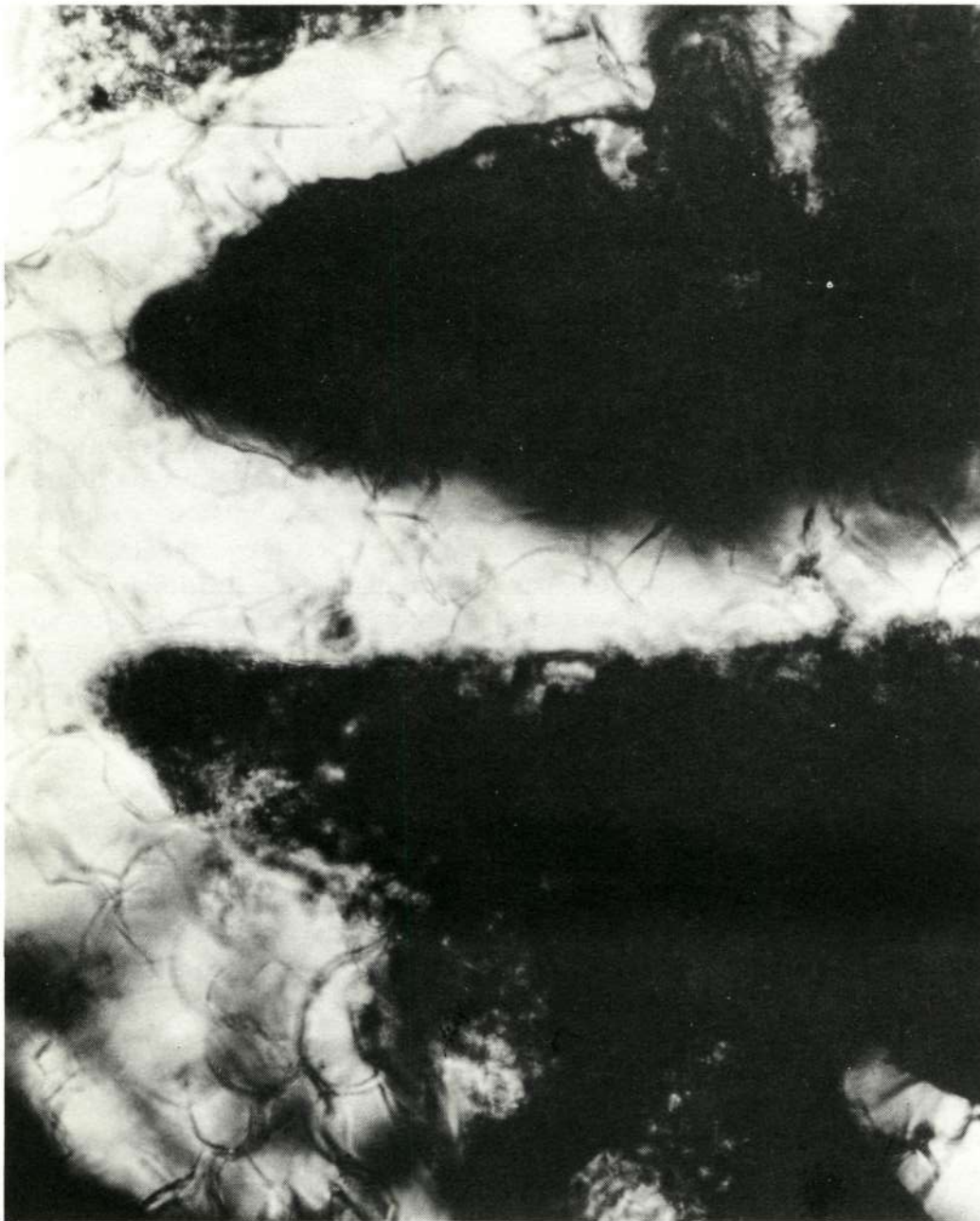


Figure 41. Unusual late-stage minerals formed by crystallization of the last residual liquid in lunar basalts, which has become highly enriched in elements like iron (Fe), silicon (Si), potassium (K), and phosphorus (P). The clear areas are cristobalite, a mineral composed entirely of silica (SiO_2). The dark areas are a mixture of glass and very fine crystals of late-forming minerals. Sample 12051; long dimension of photograph is about 0.2 mm. Photograph courtesy of L. S. Walter.



Figure 42. Small inclusion of molten liquid trapped in larger crystal in a lunar basalt while the crystal was growing. The inclusion has crystallized to form small crystals and glass. Sample 12004; the inclusion is 0.05 mm long. Photograph courtesy of L. S. Walter.



Figure 43. Large inclusion of molten liquid trapped in a feldspar crystal (white) as the crystal was growing. The trapped liquid crystallized inside the feldspar crystal to form pyroxene (gray), ilmenite (black), and cristobalite (SiO_2) (clear). Sample 12021; long dimension of photograph is about 2 mm. Photograph courtesy of L. S. Walter.

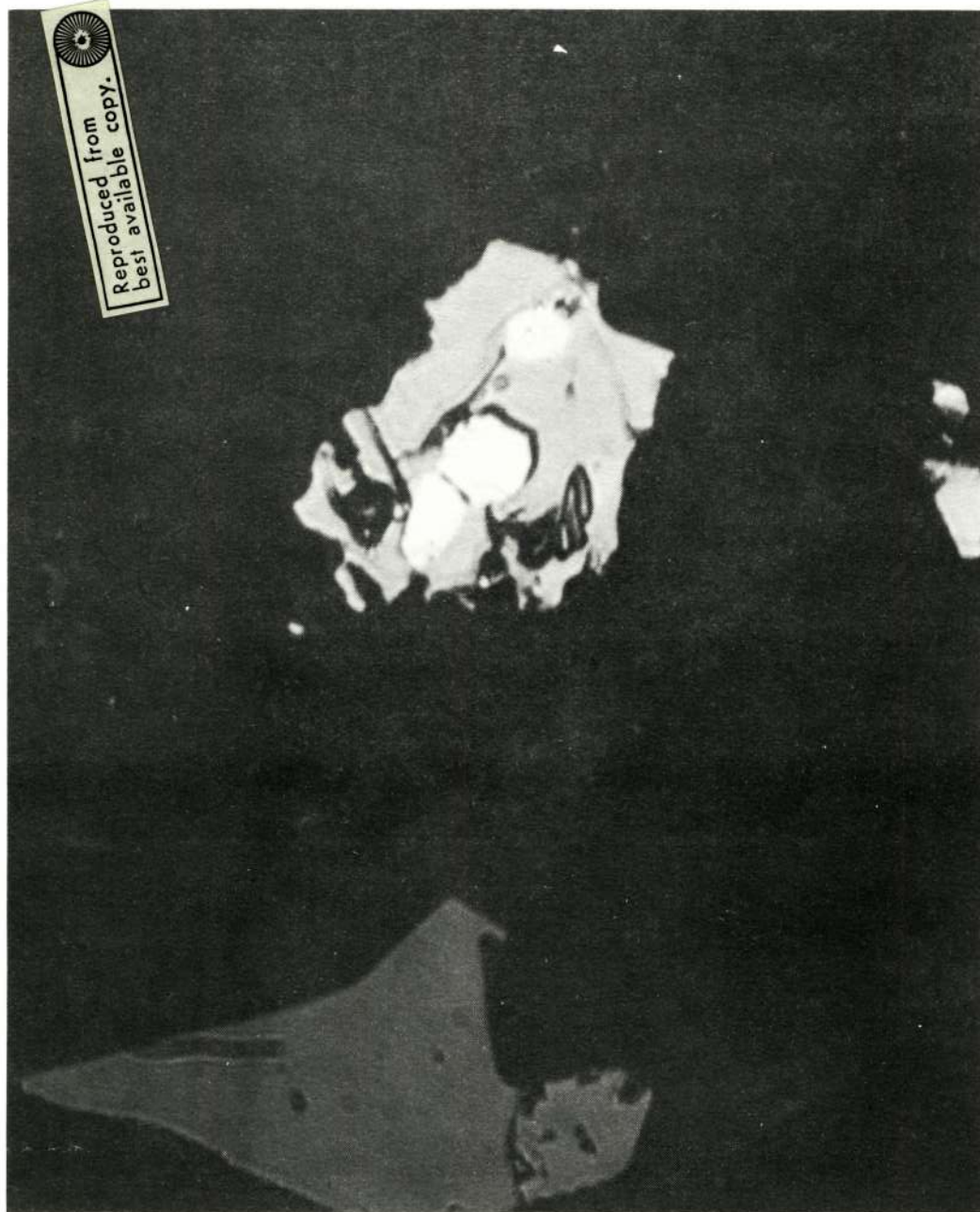


Figure 44. Opaque minerals in an Apollo 12 sample, observed in a polished thin section in reflected light. The gray crystal at left is a mineral called chrome-spinel (an Fe-Cr oxide). The lighter grain at right contains troilite (iron sulfide) enclosing small droplets of brightly-reflecting metallic Fe. The presence of Fe and troilite indicates very reducing conditions during formation of the rock. Sample 12051; long dimension of photograph is about 0.5 mm. Photograph courtesy of L. S. Walter.

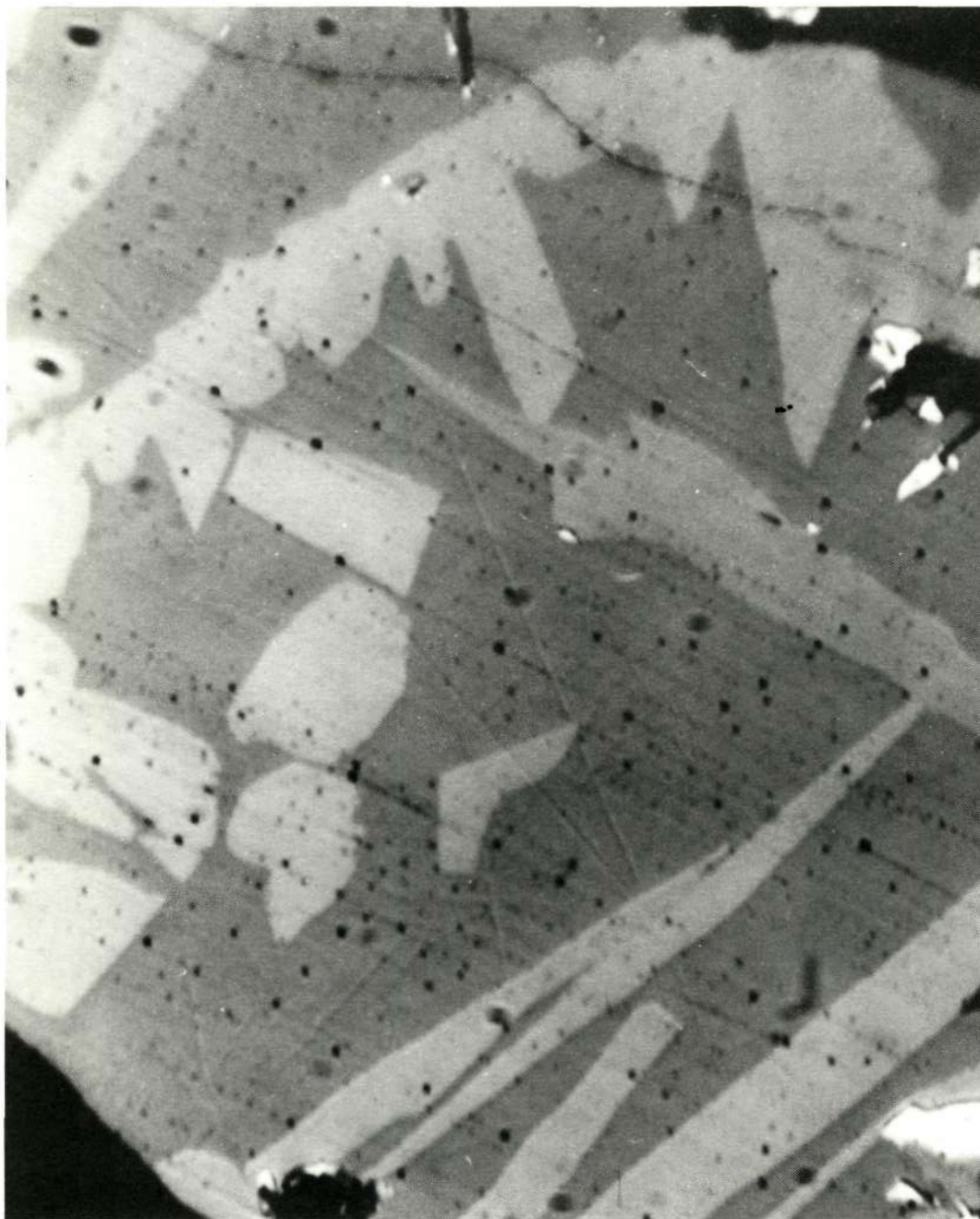


Figure 45. Reflected light photograph of a large crystal of chrome-spinel (darker gray) in an Apollo 12 sample. Crystals of ilmenite (light gray blades) are crystallizing out (exsolving) from the chrome-spinel grain, a change produced during cooling. Sample 12040; long dimension of photograph is about 0.5 mm. Small spots and fine parallel lines are polishing scratches on the section. Photograph courtesy of L. S. Walter.

FORMATION OF THE LUNAR SOIL

It is clear that the crystalline bedrock (lava flows) at the Apollo 11, 12, 14, and 15 sites has formed by cooling and crystallization of silicate melts in a manner similar to the formation of terrestrial lavas. However, once these rocks are solid and exposed at the surface, the processes by which they are broken, modified, and eroded are totally unlike anything occurring on the earth. On the earth the greatest modification of rocks takes place by weathering and erosion produced by wind and water. On the moon, where these processes are absent, one might expect that the rocks would remain unchanged since their formation.

Such durability of rocks is not the case, even on the airless moon. Because the moon has no atmosphere, even the smallest meteorite particle will strike its surface, and larger bodies, which would be burned up by the earth's atmosphere, will form craters several meters in diameter on the moon. As a result, any exposed rock on the moon is subjected to a continuing bombardment of small bodies ranging from large, crater-forming blocks meters across (which impact very seldom), to small particles a few thousandths of a millimeter in diameter (which strike the moon almost continually).

This steady bombardment has taken place over the billions of years since the lunar rocks solidified, and the result is a continuing breaking, shattering, and fragmentation of solid rock into smaller and smaller particles, forming a fragmental layer of soil (or regolith) which overlies the bedrock all over the moon. On the maria, this soil layer is a few meters thick (about a meter thick at Hadley Rille), but over the highland areas it may be as much as one or two kilometers thick. This continuing bombardment not only breaks up large blocks and outcrops, but also produces a stirring and overturning (called "gardening") of the fragmental layer already formed. Thus, large blocks may be exposed and then buried again, although the process is very slow, and many rocks exposed at the lunar surface have been there for tens of millions of years.

The existence of continuous meteorite impact on the moon is both good and bad from the point of view of doing geological work there. The "bad news" is that the fragmental layer makes it nearly impossible to collect actual bedrock, and one cannot be absolutely sure that a given rock has come from the immediate area instead of from some large crater tens of kilometers away. Only in rare cases where the soil is thin, as at the Apollo 15 site, can one be very sure that he is actually collecting bedrock in place.

The "good news" is that meteorite impact provides a way of sampling rocks from large areas of the moon by collecting at a single site. Although most of the lunar soil (95+ percent) at any given point will be composed of pieces of local bedrock, a small percentage will consist of fragments ejected from distant

craters. This fact is very important when one is limited to a small number of landing sites, because even at one site one can collect rocks from a much wider area of the moon than he could sample in person. For this reason, it has been possible to draw conclusions about the nature of the highland rocks from the exotic feldspar-rich rock fragments found in Apollo 11 soil and from the potassium-rich basaltic rocks that appeared in Apollo 12 samples.

Furthermore, a really large meteorite impact, such as the one that formed Mare Imbrium, acts as a gigantic drill and excavates samples from the deep lunar interior, scattering them on the surface where they can be collected. One of the goals of the Apollo 14 mission to Fra Mauro was to sample the unit of material ejected from the Imbrium basin (the Fra Mauro formation) in the hopes of collecting rocks that might have been excavated from as deep as 50 kilometers, material that could be obtained in no other way. The idea that even small craters excavate relatively deep material formed the basis for the Apollo 15 sampling around Spur Crater near Hadley Rille and for the Apollo 16 traverses in the Descartes region.

One of the most generally-agreed-upon conclusions of the Apollo studies is that the lunar soil or regolith has been formed by continuing meteorite impact. This conclusion is based upon very impressive observational evidence, for when meteorites strike rock at high velocities, they produce intense shock waves that in turn form unique deformational features in the target rocks and minerals. These effects, which include shattering, plastic deformation, destruction of the crystal lattice, and complete melting, cannot be produced by other geological process. The occurrence of these effects in the lunar soil is conclusive evidence for its formation by meteorite impact. Some of these effects are shown in the pictures that follow.

Because the lunar soil is formed by the continuous breaking up and melting of rocks, the lunar soil is composed of a wide variety of rock fragments, melted rocks, and mineral grains in various stages of destruction by shock waves. Figure 46 shows some of these particles, about a millimeter in size, that were separated from the Apollo 11 soil. There is a great variety: small fragments of crystalline rocks; slaggy-looking particles composed of mixtures of rock fragments and glass produced by melting; mineral grains like the white feldspar grain, which have been converted into a glassy material by the shock waves; and actual droplets of melted glass that form spheres and dumb-bell-shaped particles. Some of these glass droplets are shown in Figure 47. They come in a wide range of colors and chemical compositions, which indicates that they formed by melting of the lunar rocks by meteorite impact rather than from volcanic eruptions.

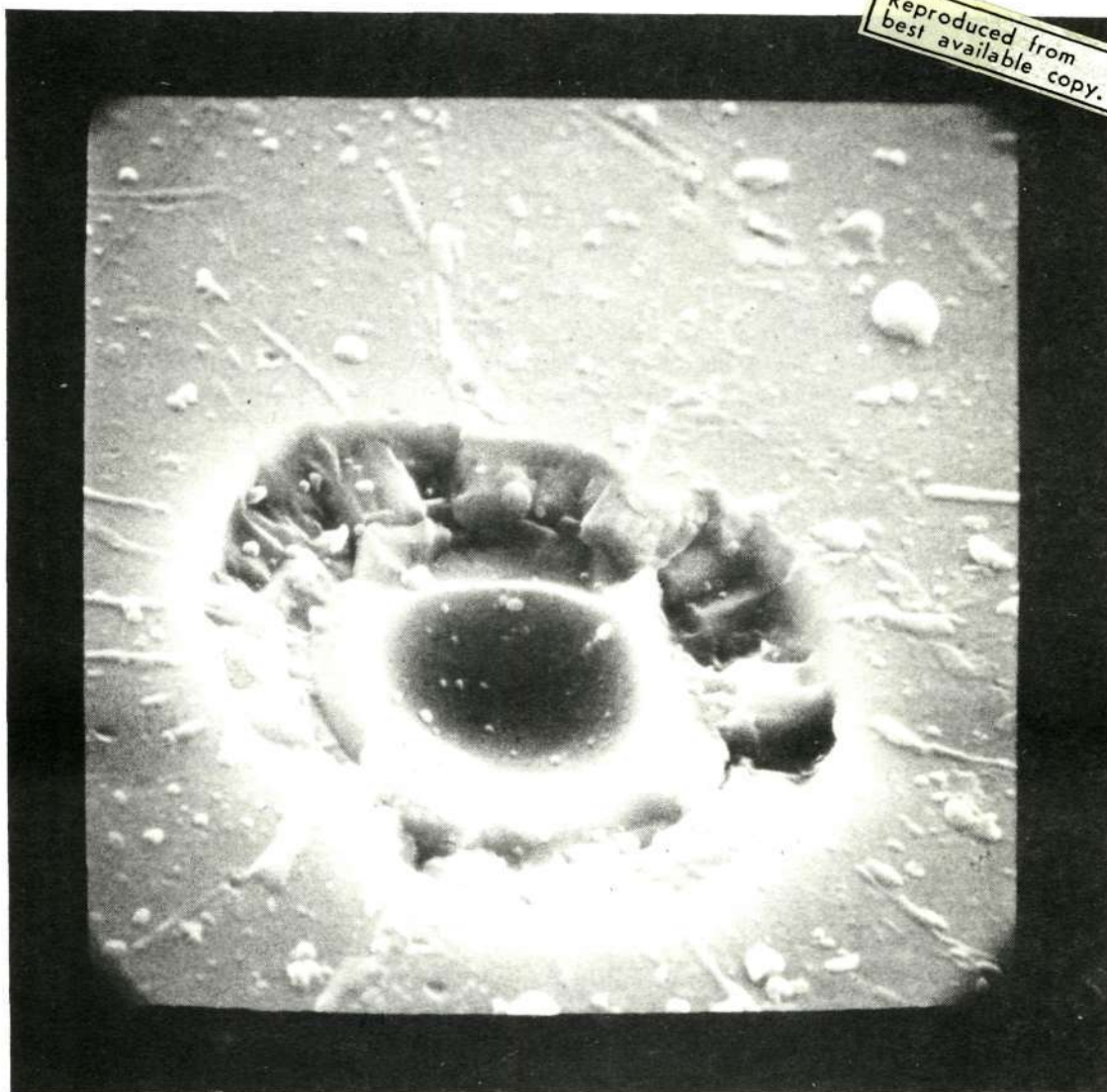


Figure 46. Photograph of small particles separated from the Apollo 11 lunar soil. Particles are between 1 and 4 mm in size. Different types of material present include: (1) fine-grained crystalline basaltic rocks; (2) feldspar altered to glassy material by impact-produced shock waves; (3) slaggy and cindery particles made up of rock fragments and impact-produced glass; (4) free-form glassy droplets. Divisions on scale bar (lower left) are 1 mm. Photograph courtesy of J. A. Wood.



Figure 47. Small glass droplets separated from the Apollo 11 soil, together with small rock fragments in a metal sample tray. Note the range of colors in the droplets, from very dark (lower center) to clear (upper center). Lines on the background are scratches on the metal tray. The largest glass droplet is about 0.5 mm in diameter. NASA photograph S-69-45182.

The bombardment of the lunar surface continues down even to very small particles which make craters less than a millimeter in diameter. These micro-craters (sometimes called "zap craters") (Figure 48) have been found on the surfaces of lunar rocks and can be used to calculate how long the rock has been exposed at the surface. This picture shows a crater only a few tenths of a millimeter across. The inner, glass-lined crater is surrounded by a larger circular fracture, and melted material from within the crater has been sprayed out beyond the rim.



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Figure 48. Scanning electron microscope photograph of a small micro-meteorite impact crater ("zap crater") in the surface of the lunar sample. The crater consists of an inner glass-lined pit about 0.1 mm across, surrounded by a larger ring formed when material was chipped off (spalled) by the impact. Note the spray of small molten rock droplets (white) that have been ejected from the center of the crater. Photograph courtesy of J. B. Hartung.

This same high degree of fragmentation and melting caused by meteorite impact is also seen in a type of lunar rock called microbreccia, a name which just means that it is a rock composed of many small fragments of different kinds. Some scientists think that the microbreccias were formed by the compaction of loose lunar soil, while others suggest that they formed by the deposition and welding of a cloud of very hot particles ejected from a meteorite crater.

A typical Apollo 11 microbreccia is shown in Figure 49; the slice or thin section is about 2 centimeters in diameter. The rock is composed of very small fragments which, on closer inspection, turn out to be bits of rock and mineral grains, melted glassy fragments, and pieces of shock-deformed minerals. The very dark color is produced by fine powdered ilmenite, the opaque minerals in the lavas, which is so black that even a small amount of it, mixed in with the other rock and mineral fragments, is enough to color the mixture black.

The next few pictures show some of the different shock effects observed in small fragments in the lunar microbreccias. Figure 50 shows a small fragment of light yellow-brown glass about 0.2 millimeters long. The glass is not uniform, and there are swirly flow lines running through it. Two small mineral fragments (the white spots) are included in the glass. This nonuniformity of the glass and the inclusion of rock and mineral fragments is typical of glasses produced by meteorite impact.

Figure 51 shows a somewhat different effect on a grain of feldspar about 0.4 millimeters long. This fragment has been strongly deformed by shock waves, but not strongly enough to produce complete melting. In this first figure, seen in ordinary transmitted light, the clear character of the crystal is visible. The fine lines are so-called "twin" crystals that were part of the original grain before it was shocked. Notice also the clear area in the upper right part of the grain. Examination of the same grain in polarized light (Figure 52), shows something very important. Some of the twin crystals and the clear area are completely dark, while adjacent twin crystals are bright. The bright areas are still crystalline, which means that their original ordered arrangements of atoms has been preserved. But in the dark areas, the ordered crystal structure has been destroyed by the shock wave, producing a substance like glass but without melting. You can see from the picture that this destruction, shown by the dark areas, is very selective and only occurs in parts of the original grain. This kind of selective destruction of the crystalline structure is a unique kind of deformation that is produced only by intense shock waves associated with meteorite impacts. This kind of evidence, which you can observe easily through the microscope, is good evidence that the lunar soils and microbreccias have been produced by the action of meteorite impacts over billions of years.

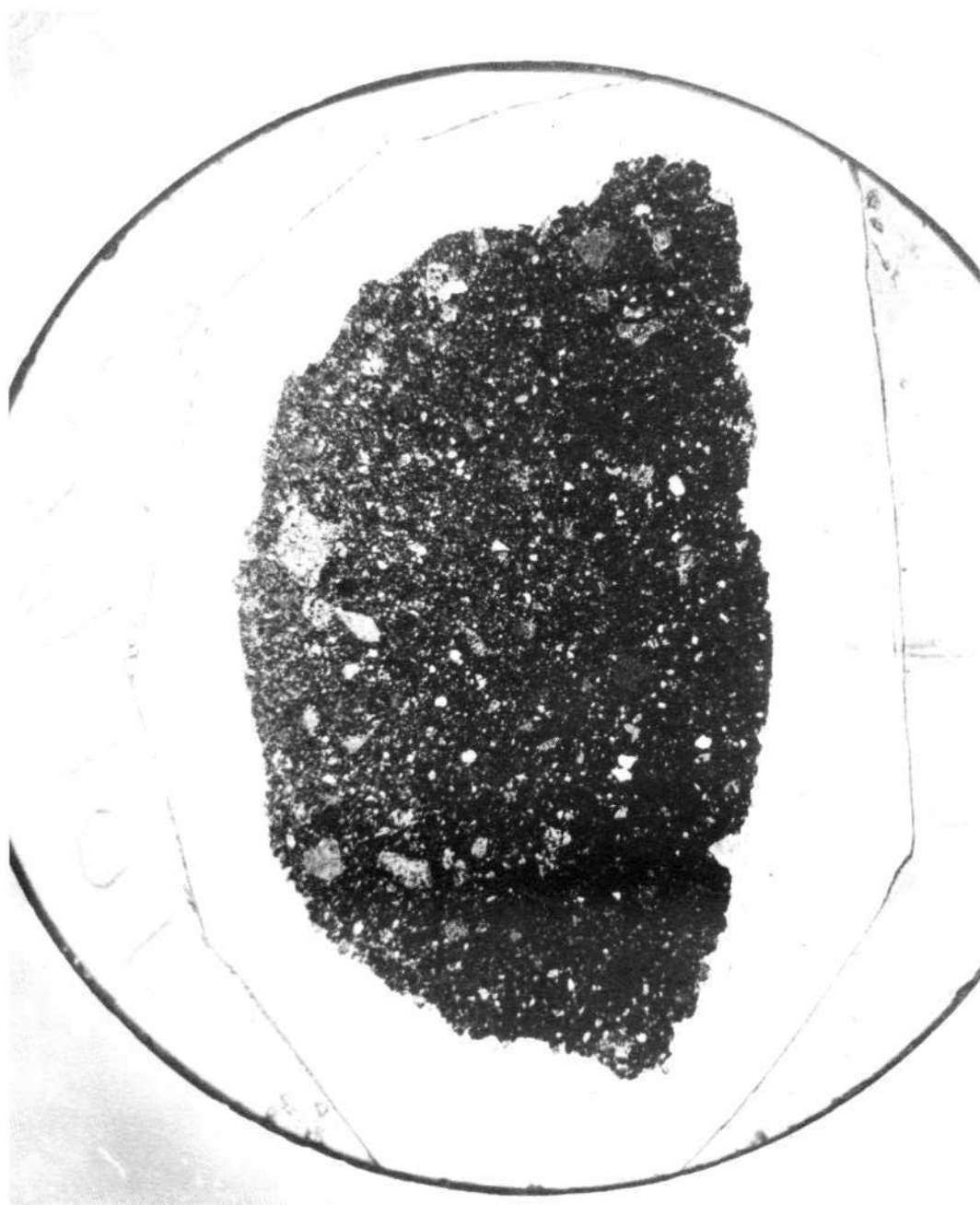


Figure 49. Photograph of thin section of Apollo 11 microbreccia. The rock is composed of small fragments of rocks, minerals, and glass in a fine dark matrix. Note the teardrop-shaped glass fragment in the upper center of the specimen. Specimen 10060; the circular glass section is 1 in (25.4 mm) in diameter.

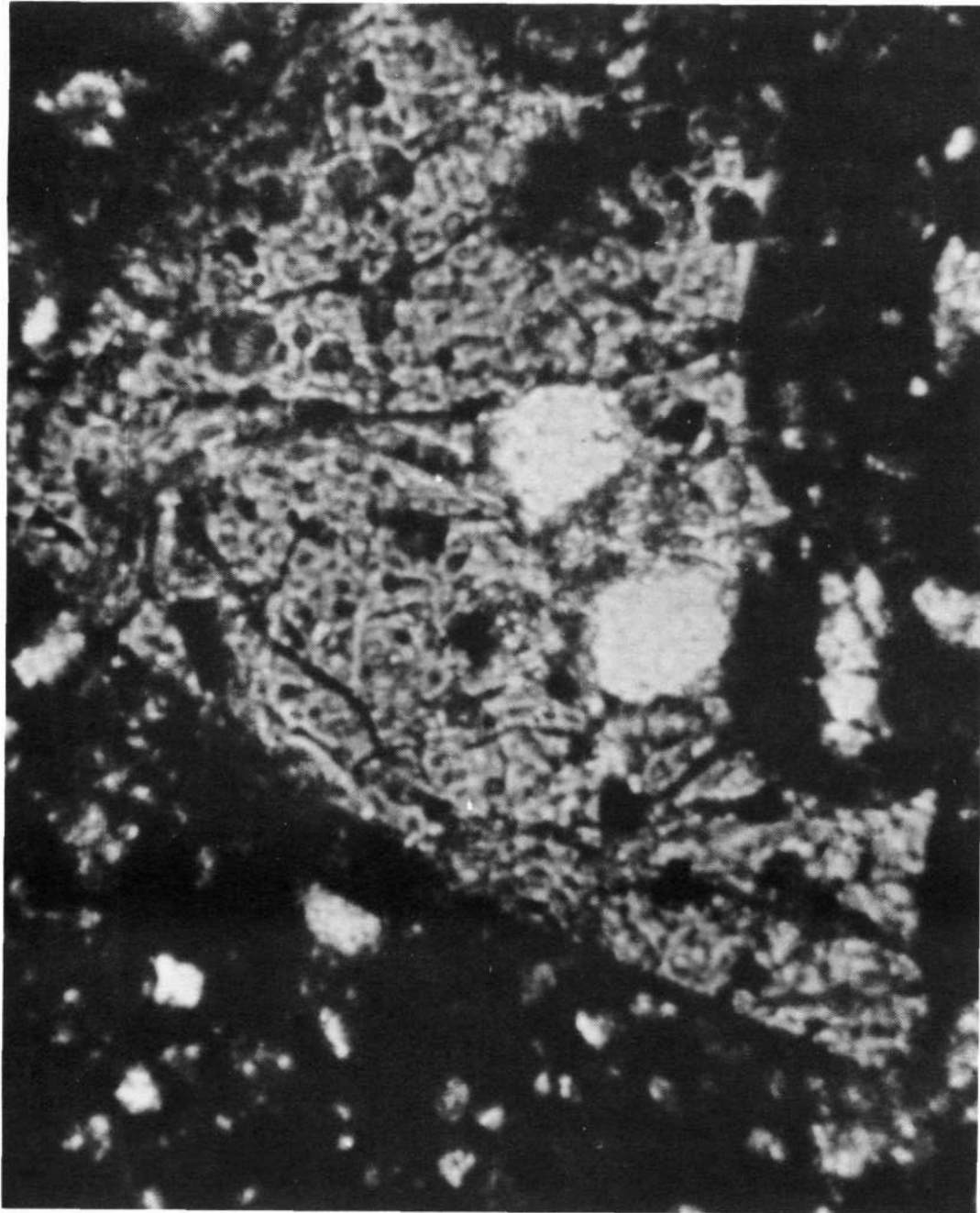


Figure 50. Fragment of yellow-brown shock-melted glass in an Apollo 11 microbreccia. The glass, which was formed by melting of rocks by meteorite impact, is not uniform and shows flowed areas of slightly different colors. Two mineral grains (white spots) were engulfed by the glass while it was molten. Sample 10060; long dimension of photograph is about 1 mm.

SOME LATER APOLLO ROCKS

Each Apollo mission has brought back something different. Our knowledge about the kinds of rocks on the moon has increased in large jumps with each mission, not only because of the different rocks brought back, but also because we have been able to fit the results of each new mission into the framework of information produced by previous missions.

The rocks of Apollo 12 were somewhat different from those returned by Apollo 11. They were still lunar lava flows, but they were considerably younger (about 3.3 billion years old) and more diverse in mineral composition. The rocks of Apollo 14 were again quite different from both Apollo 11 and Apollo 12 samples. For one thing, they were mostly breccias, or rocks composed of pieces of other rocks and minerals, and only two crystalline igneous rocks were returned. The Apollo 14 mission apparently sampled the great layer of material ejected from Mare Imbrium, and its rocks therefore represent an extremely complicated story. The Apollo 15 mission returned the largest geological haul to date, a fascinating suite of crystalline rocks, breccias, "green glassy rocks," and diverse soils which are just now beginning to be studied.

However, although the later rocks may be different and more complex than those returned by the early Apollo missions, the methods of studying them are the same. Scientists are still preparing thin sections and studying them with the microscope and the electron microprobe in the same ways that I have described for the Apollo 11 samples. And just to bring you a little more up to date, the next few pictures show some of the rocks returned from the Apollo 14 mission to Fra Mauro.

Figure 53 shows one of the two crystalline rocks returned from Fra Mauro by the Apollo 14 astronauts. It has the same kind of igneous texture that you have seen in the Apollo 11 rocks and is composed of the same minerals, gray pyroxene, white feldspar, and black ilmenite. However, there is much more feldspar and much less opaque minerals in this rock than there were in the Apollo 11 specimens. This is a very important discovery, because it shows that there are at least two different kinds of lavas on the moon. One kind, which occurs on the maria, contains less feldspar and more Fe-Ti minerals, while this Apollo 14 lava contains more feldspar and much less Fe and Ti. Because feldspar contains a great deal of aluminum, this second kind of basalt ("nonmare" basalt) is much richer in aluminum than are the mare basalts, and this rock may be similar to the rocks that make up the lunar highlands, which the Apollo 15 orbital science experiments showed to have much more aluminum than do the maria. So, by putting together the rocks from Apollo 11 and Apollo 14 and the orbital science data from Apollo 15, we are already starting to learn a lot about the chemistry and rock types over large parts of the moon.



Figure 51. Fragment of feldspar, highly altered by shock waves, in an Apollo 11 microbreccia. The feldspar crystal, probably from a broken lunar basalt, shows faint nearly-vertical lines (twin planes) that were present in the original crystal. Sample 10060; long dimension of photograph is about 1 mm.

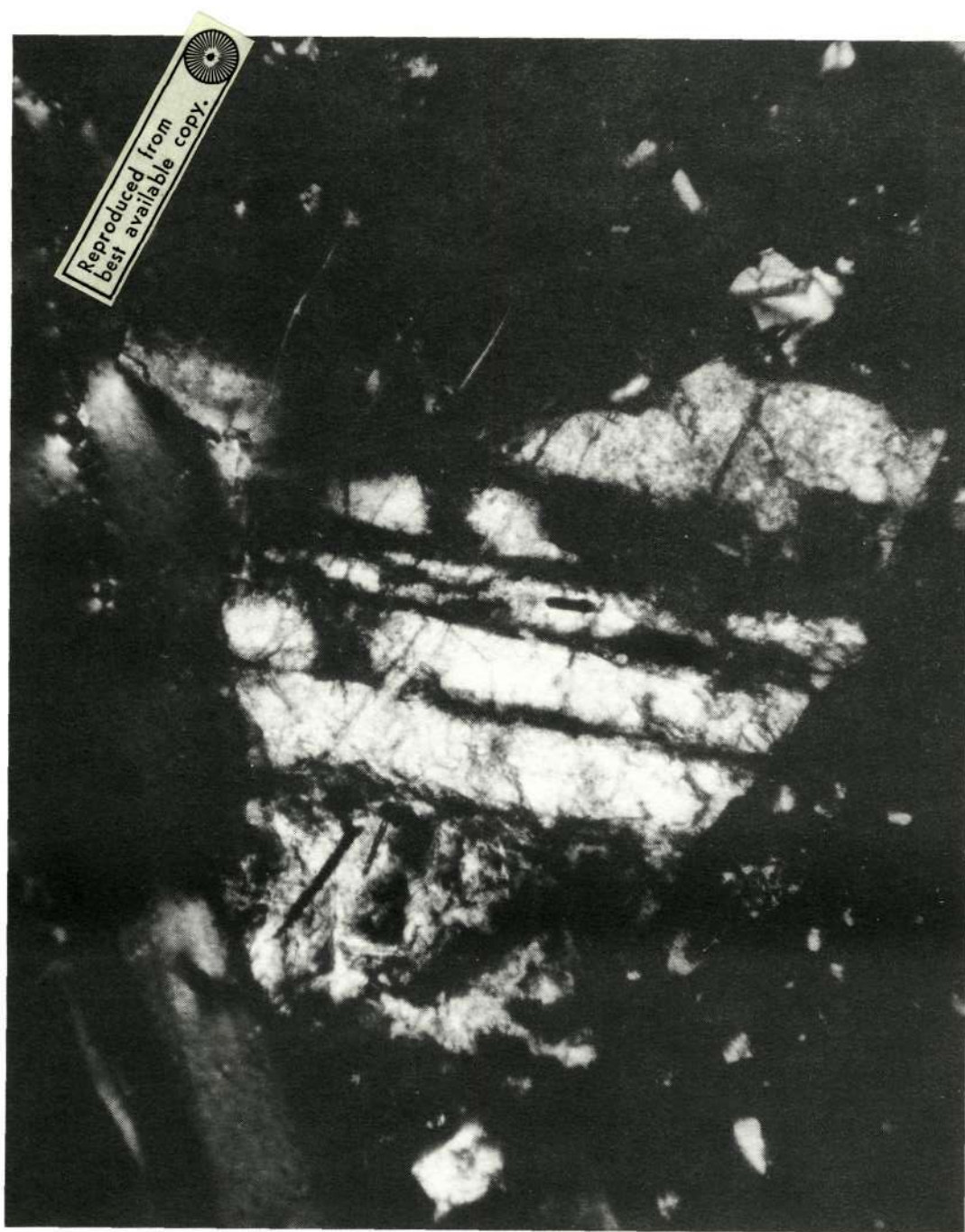


Figure 52. Same view as Figure 51, but in polarized light. Parts of the crystal have been altered by the shock waves to a glassy material that appears dark in polarized light. Other areas of the grain still retain their crystal structure and appear bright. Note that the clear area (upper right in Figure 51) is entirely black, and that the black areas extend through the entire grain.

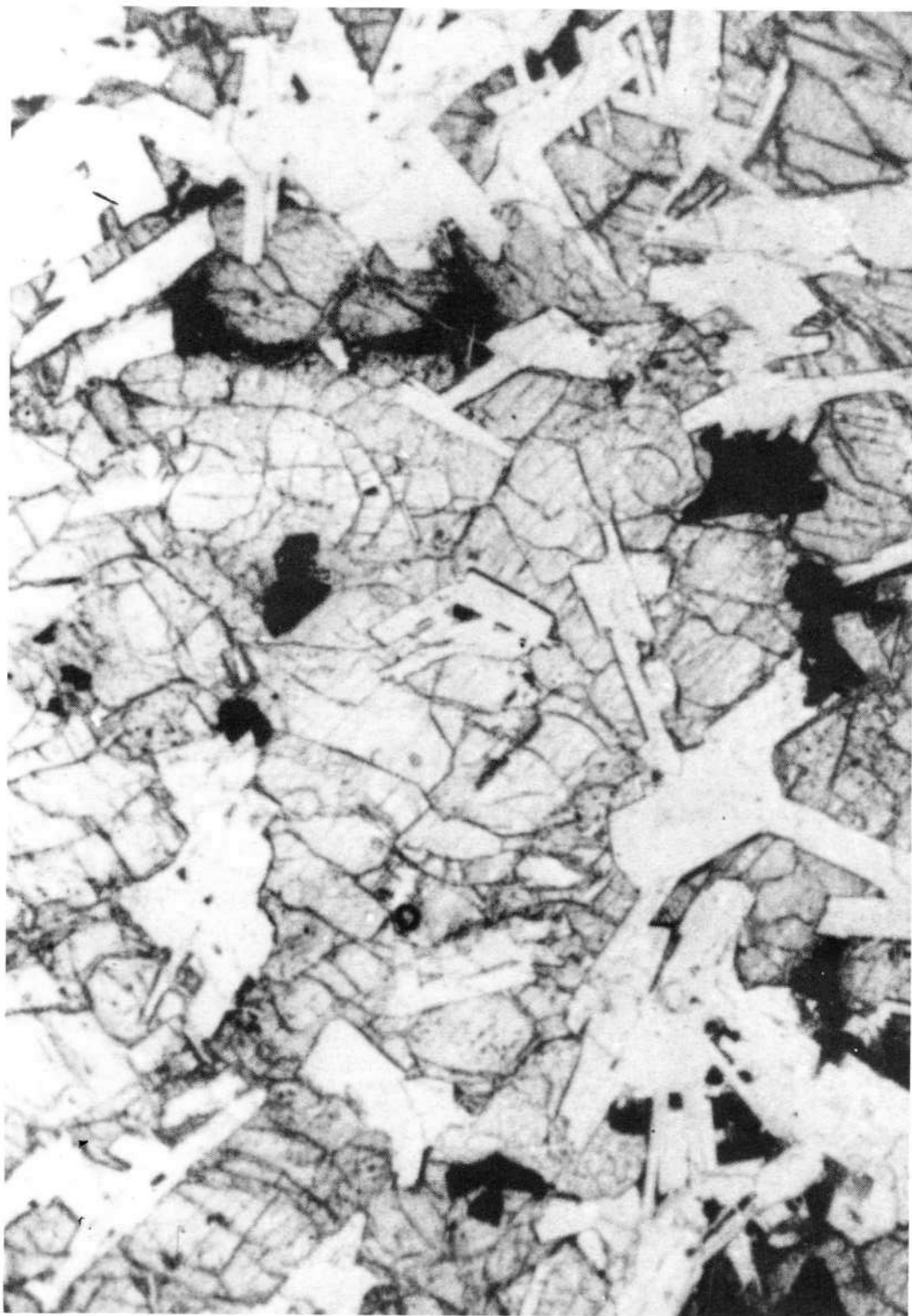


Figure 53. Thin section of basalt collected from the Fra Mauro landing site of Apollo 14. These basalts are composed of the same minerals as are the mare basalts sampled by Apollo 11 and Apollo 12; pyroxene (gray), feldspar (white), and ilmenite (black). The Apollo 14 basalts, however, contain more feldspar and much less ilmenite than do the mare basalts, and they are therefore higher in Al_2O_3 and lower in TiO_2 (compare with Figures 35 and 36). Sample 14053; long dimension of photograph is about 0.5 mm. NASA photograph S-71-23778.

Only a few of the Apollo 14 rocks are crystalline lava flows made up of individual crystals of pyroxene, feldspar, and ilmenite. Most of the Apollo samples are breccias, which is a term used to describe a rock composed of different fragments of rocks and minerals all mixed together (like concrete). (When the individual fragments are very small, the term microbreccia is used, as for some of the Apollo 11 samples.)

A typical Apollo 14 breccia is shown in Figure 54. It is composed of many dark rock fragments in a gray matrix. A microscopic thin section of one of these breccias (Figure 55) shows that it contains many rock fragments that are similar to the feldspar-rich basalt lava shown in Figure 53. The sample of breccia shown in Figure 56 is more complicated. In this rock, several of the individual fragments themselves resemble the Apollo 11 microbreccia samples, and thus we have a complicated series of "breccia-within-breccia" in these rocks. This complexity tells us that the Apollo 14 rocks record more than one period of breakup and mixing of rock fragments to form breccias, and the details of this complicated history have yet to be fully understood.

As a familiar note, the Apollo 14 breccias also contain glass droplets (Figure 57) similar to those found in breccias from the other landing sites and also formed by meteorite impact.

In contrast to the breccias that make up most of the Apollo 14 rock samples, the Apollo 15 mission returned a wide variety of both crystalline rocks and breccias from Hadley Rille and Apennine Front. Figure 58 shows an extremely porous specimen of lava collected from near Hadley Rille. The numerous large bubbles were formed by escaping gas as the rock solidified, and the frothy character of this rock indicates that the lava was quite gas-rich and cooled fairly rapidly, possibly as the outer surface of a lava flow. The unusual breccia shown in Figure 59 is the so-called "Black-and-white rock." It consists of pieces of coarsely-crystalline basaltic rock in a dark matrix which consists of very finely-crystalline basalt. It is possible that the dark matrix may have been produced by melting of the white basalt by a meteorite impact event.

All these studies of the appearance and the nature of the Apollo samples described here are being complemented by detailed studies on the chemistry, age, and physical properties of the samples. Although the Apollo landings themselves will end this year with the missions of Apollo 16 to Descartes and of Apollo 17 to Littrow, the study of the samples is only just beginning. We have, with these early landings, already learned much about the moon, and we have made some fundamental discoveries about its origin and history. The last missions, with their larger scientific payloads, will provide us with even more material. And the greatest payoff will come in the years ahead, as scientists continue to work with the samples that have been returned, fitting the new data into what we already know about the moon.

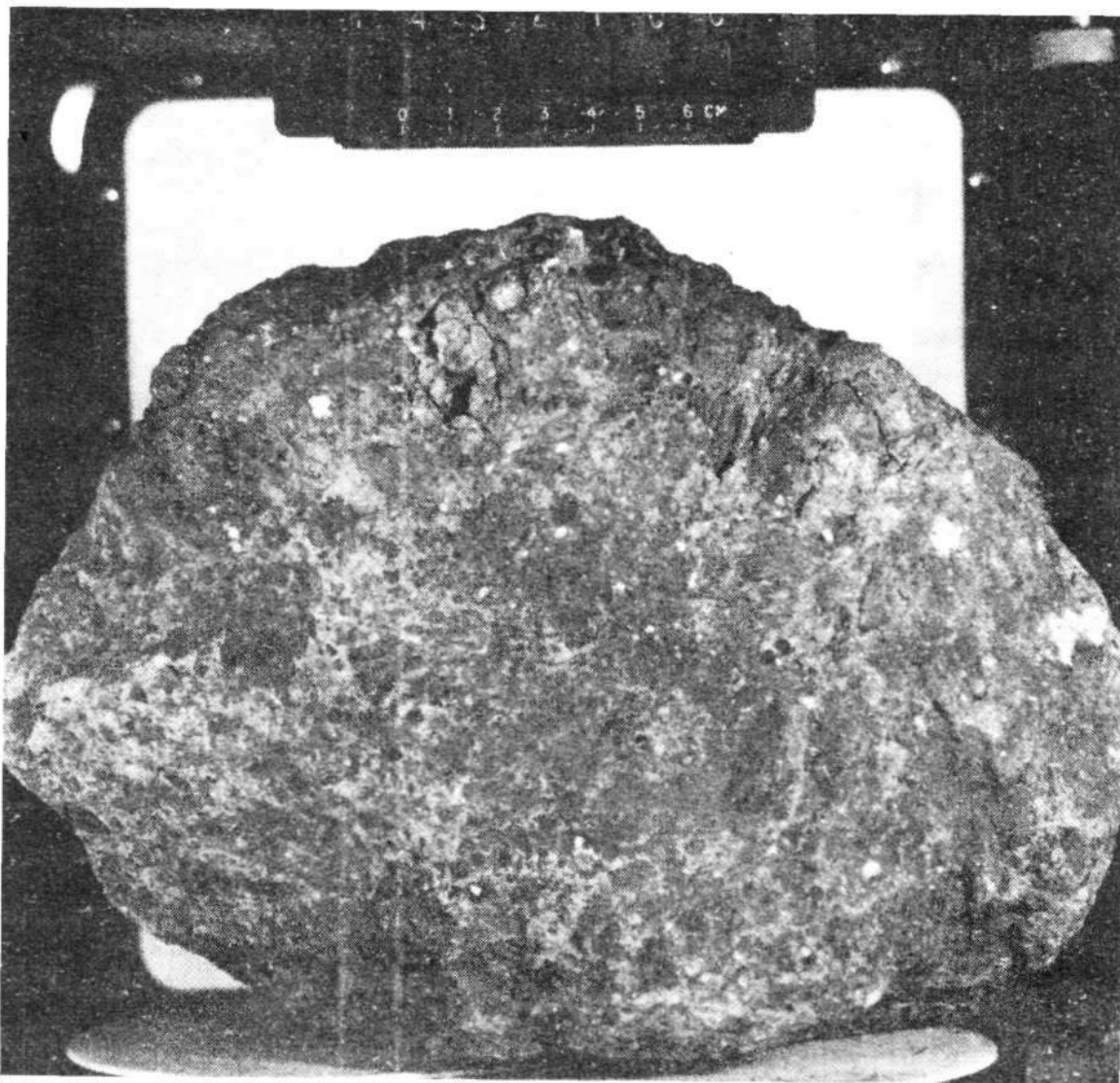


Figure 54. Photograph of a typical Apollo 14 breccia specimen. This rock, called "Big Bertha," weighs about 20 lbs and was the largest specimen returned from the Apollo 14 mission. It is composed of dark irregular rock fragments in a lighter gray matrix. Sample 14321; scale bar at top is in centimeters. NASA photograph S-71-56345.

THE NEW MOON

Just like Galileo's telescope, the study of the moon by the Apollo program has raised more questions than it has answered. We have already learned many definite facts about the moon that we could never have learned without going there (see Appendix). We have not yet answered the big question about exactly how it formed, and the "daughter," "sister," and "mistress" theories still have their supporters. However, we do know that the moon has existed as an independent body for more than 4 billion years, so that if it did separate from the earth,

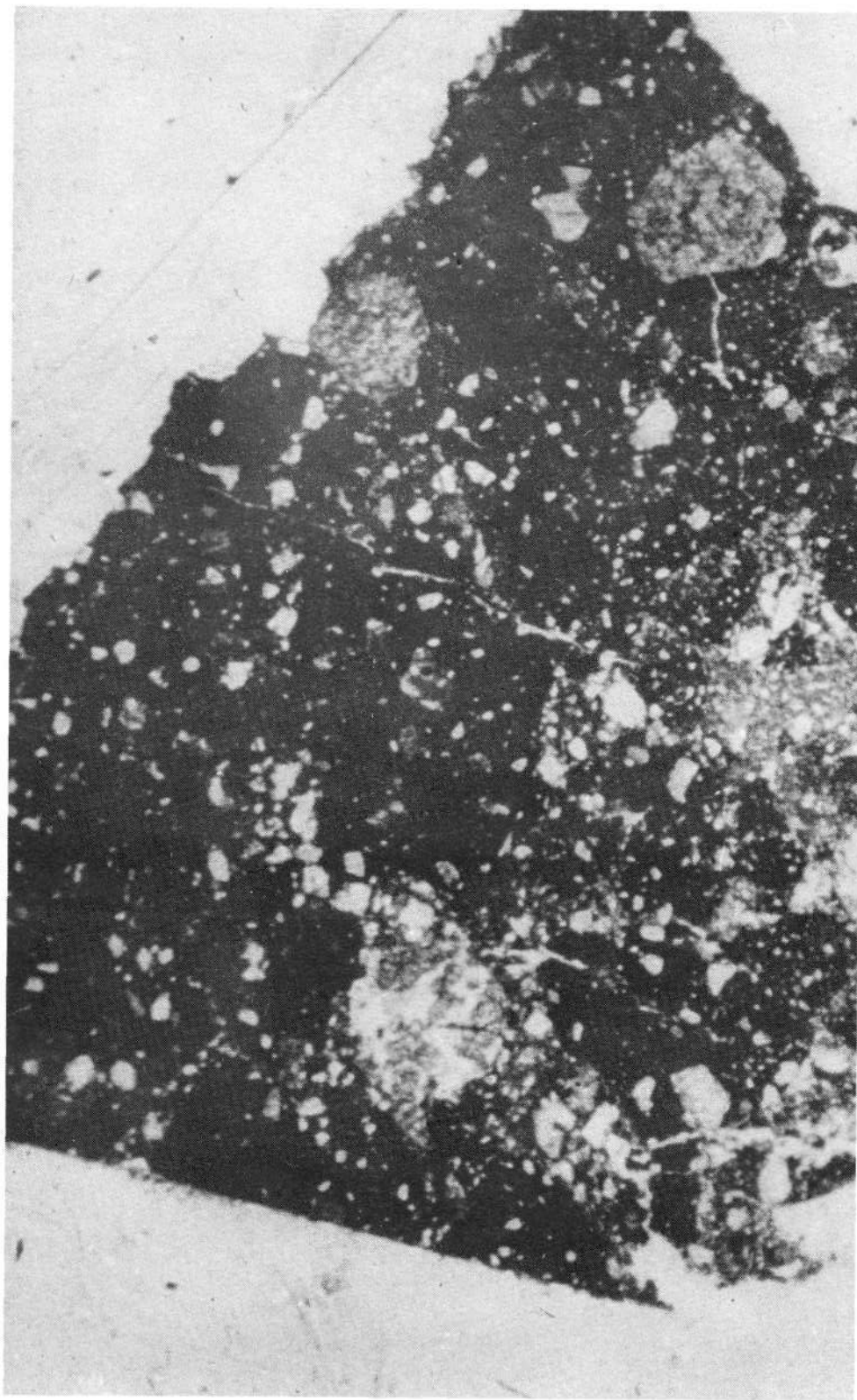


Figure 55. Thin section of Apollo 14 microbreccia which consists of diverse light-colored crystalline rock fragments (basalts and anorthosites) in a fine dark matrix. Sample 14306; long dimension of photograph is about 15 mm. NASA photograph S-71-23793.

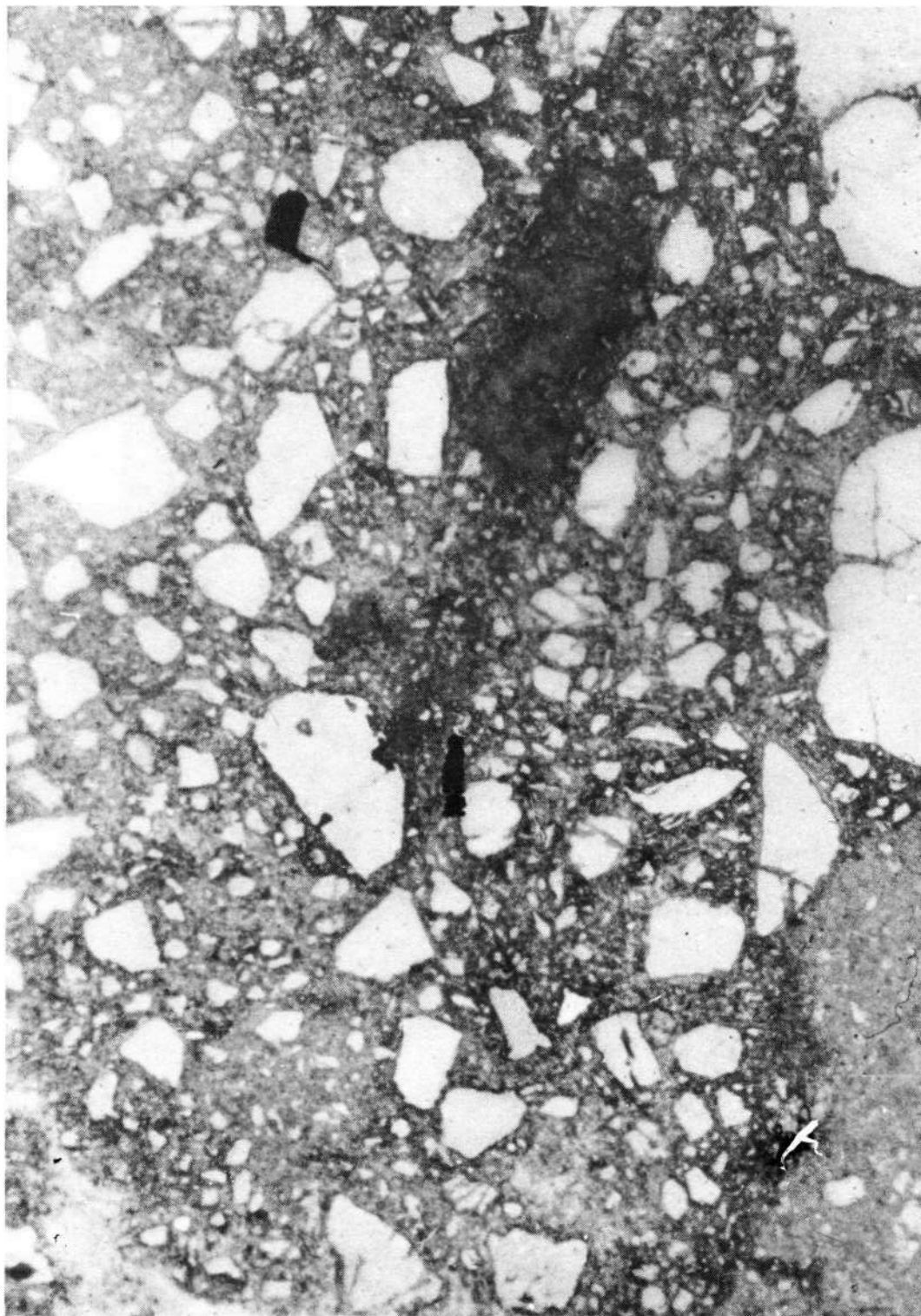


Figure 56. Thin section of lighter-colored Apollo 14 microbreccia, containing angular broken crystal fragments in a light-colored, glass rich, partly welded matrix. Notice the glass-rich breccia fragment with small grains (lower left) that occurs as a separate fragment in the larger breccia sample. Sample 14082; long dimension of photograph is about 2 mm. NASA photograph S-71-23784.



Figure 57. Broken droplet of impact-melted glass from an Apollo 14 microbreccia sample. The droplet is similar to fragments seen in the Apollo 11 and Apollo 12 microbreccias. Such droplets, however, are relatively uncommon in the Apollo 14 breccias. Sample 14307; long dimension of photograph is about 0.5 mm; NASA photograph S-71-23801.

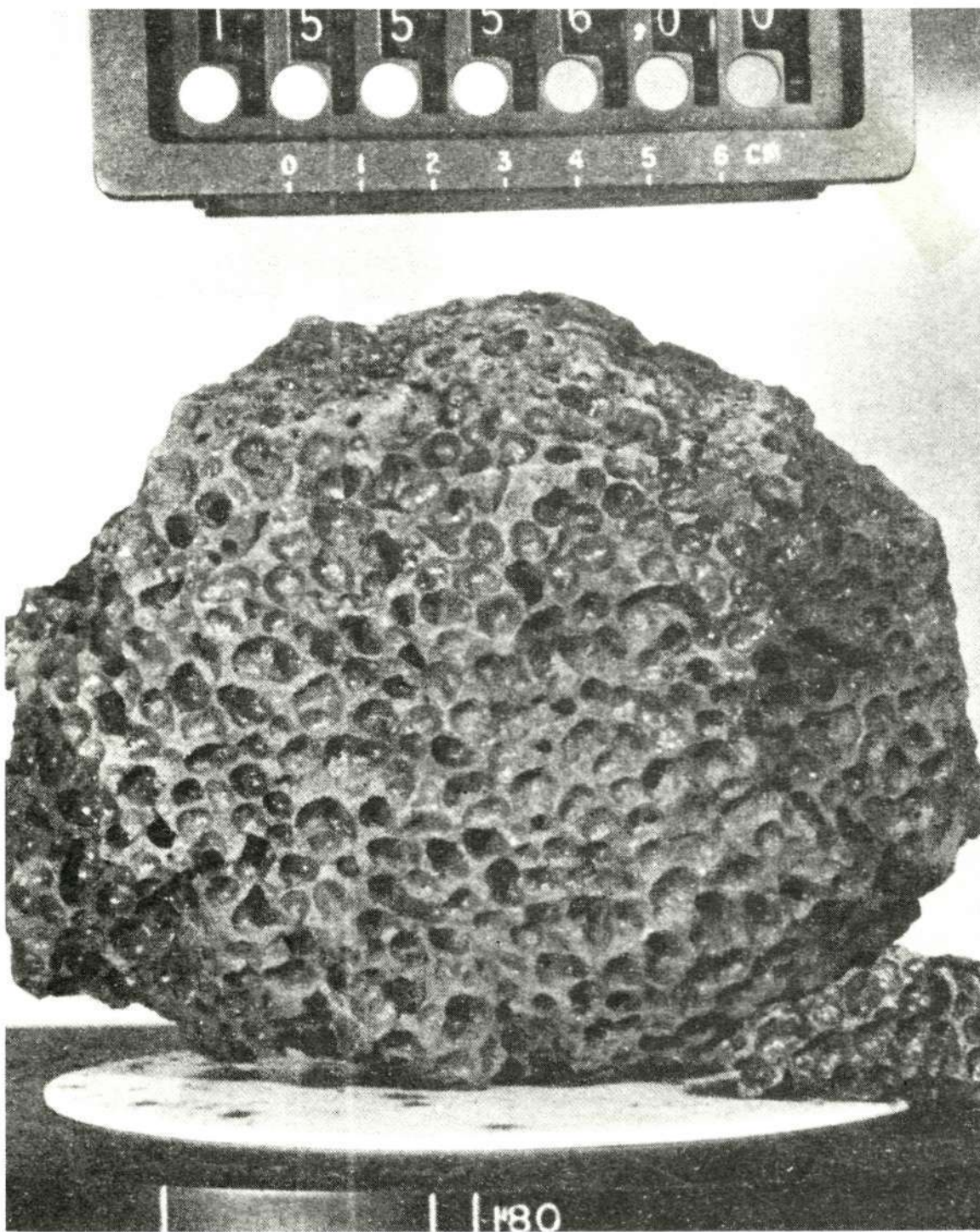


Figure 58. Large specimen of extremely vesicular mare basalt collected on the Apollo 15 mission. The numerous glazed bubbles (vesicles) in the specimen indicate that the rock was very gas-rich and frothy while cooling. Sample 15556; scale bar at top is in centimeters. NASA photograph S-71-43328.

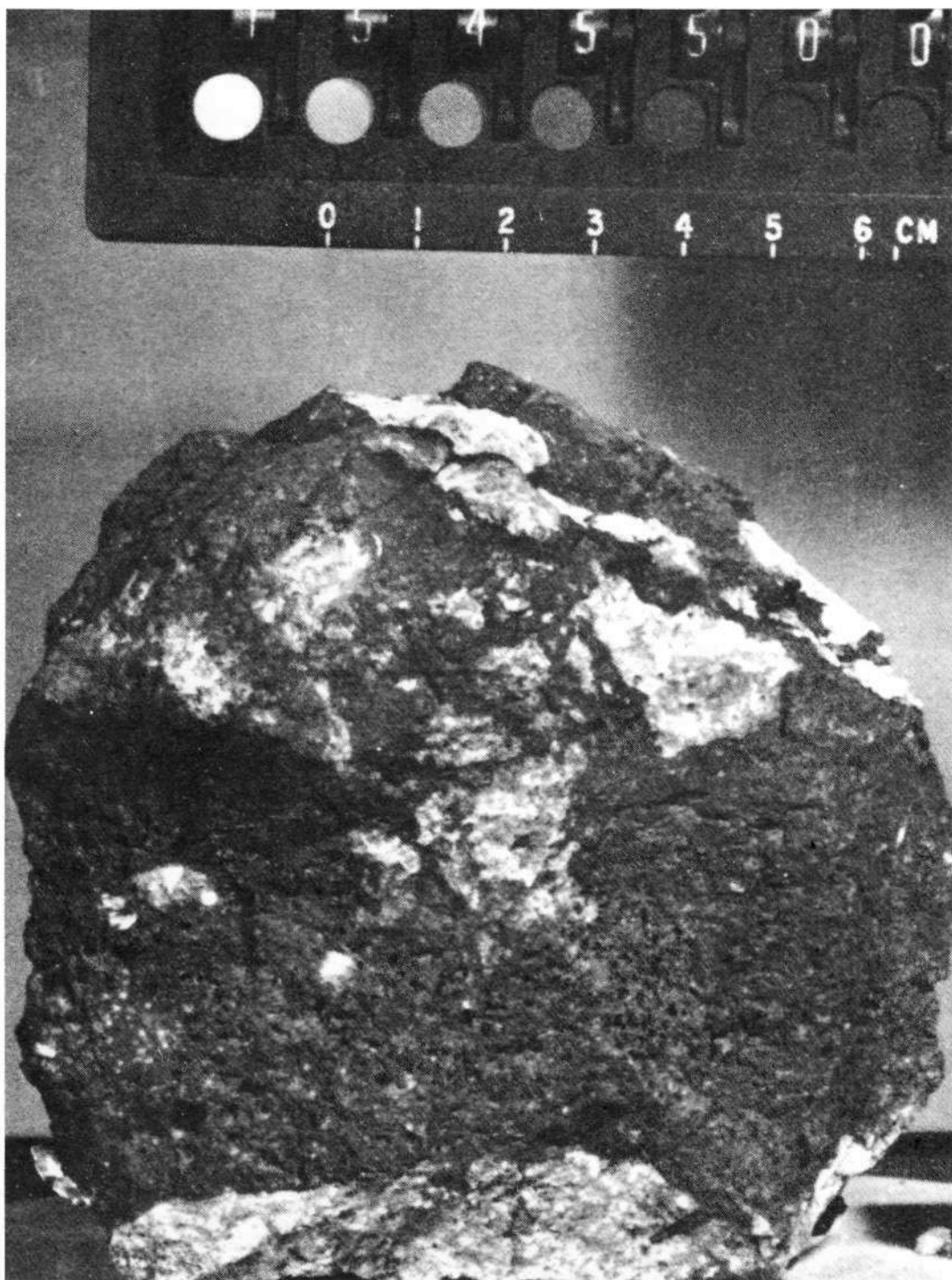


Figure 59. The unusual "Black and White Rock" collected on the Apollo 15 mission near the Apennine front at Spur Crater. The specimen contains white fragments of medium-grained basaltic rock in a dark matrix with numerous bubbles (vesicles). The dark matrix is a finer-grained basaltic rock that may have been produced by impact melting of the coarser white material. Specimen 15455; scale bar at top is in centimeters. NASA photograph S-71-43889.

this separation must have taken place much farther back in the past than anyone had thought. If the Apollo results have not definitely proven any one theory of origin for the moon, they have tended to weaken the fission ("daughter") theory and, to a lesser extent, to weaken the capture ("mistress") theory as well. As study of the moon continues, we will approach a better idea of its origin, not by definitely proving one theory, but by collecting facts that make alternate theories less likely.

As this rethinking of lunar origins is continuing, let us try and summarize this new moon as we see it in the light of the Apollo missions. Figure 60 is a view of it from Apollo 8, as no earth-bound man could ever see it, with the dark maria on one side and the highlands on the other stretching into the once-mysterious back side. What have we learned?

1. The moon is very old. The rocks of the maria, which are the youngest features on its surface, are from 3.3 to 3.7 billion years old. The heavily cratered highlands, therefore, are older, probably more than 4 billion years old, and they may go back to the original formation of the moon, 4.6 billion years ago. It is clear from these data and the pictures, that the moon had a very busy time during its first half billion years.
2. The moon is now very quiet. The Apollo seismometers, which detect "moonquakes" in the lunar interior, record only very small events, many less than would be present in the earth. Some of these small quakes seem related to tidal stresses in the moon and are apparently produced as the moon swings in its orbit around the earth.
3. The moon has a very weak magnetic field. Magnetometers on the moon measure a magnetic field less than one per cent as strong as that of the earth. But even this field is much stronger than scientists expected, and there is no general agreement about what it means. One possibility is that the moon has a very small core of nickel-iron like the earth's, and another idea is that the surface rocks inherited the magnetic field from the earth or the sun at some time in the past. No one is really sure.
4. The moon has a fragmental surface layer formed by meteorite bombardment. Rocks exposed on the lunar surface for billions of years have been broken up, worn down, and melted by steady bombardment of large and small meteorite particles, producing a lunar "soil" that is totally unlike anything formed on earth.



Figure 60. View of the moon from Apollo 8. The earth-facing side is at lower left, while the upper right shows the light highlands areas of the back side. The dark circular mare at left is Mare Crisium. Langrenus is the large bright crater in lower center, and Tsiolkovsky (see Figure 18) is the small dark spot at the upper right edge of the moon. NASA photograph AS-8-2506.

5. The moon was once hot enough to melt its interior. This was one of the first results from the Apollo 11 samples and one of the most important. It showed that the moon had not been a cold, lifeless body since its formation, and that at least once, 3.7 billion years ago, it had been hot enough to produce molten rock in its interior and spread it over Mare Tranquillitatis as lava flows.

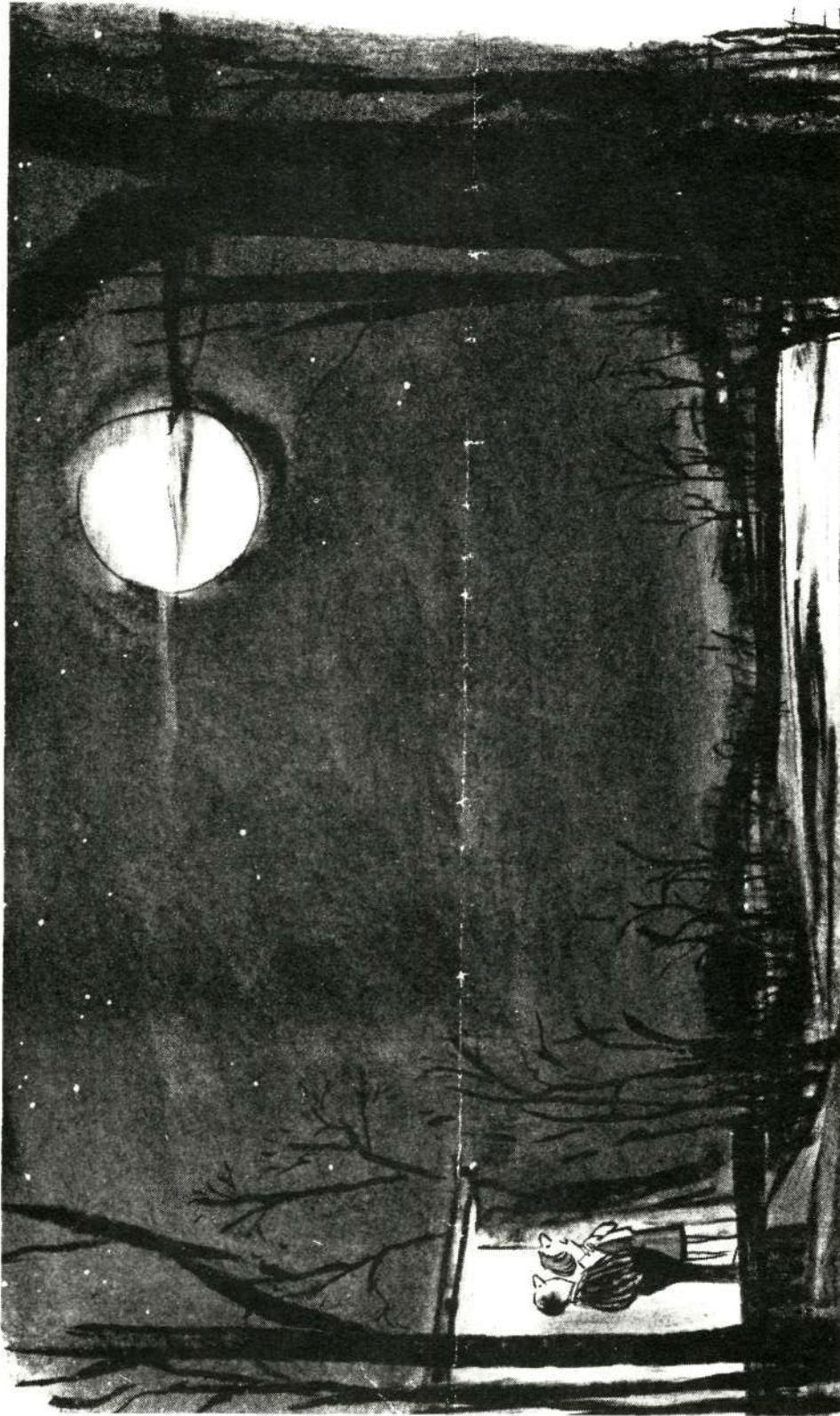
We now know that the moon was hot for a relatively long period of time, because molten rocks from different landing sites range in age from 3.3 billion years (Apollo 12) to almost 4.0 billion years (Apollo 14). This problem of getting the moon hot and keeping it hot for more than half a billion years is one of the most difficult to explain in any theory of formation. Another problem is that the moon may still retain some of its heat, possibly contributing to the so-called glowing "lunar transient events" that have been observed and which may be emissions of hot gas from the lunar interior.

But in spite of its hot and active youth, the moon as we see it today is a very cold, quiet, and unfriendly place. There is no wind, no water, and no active mountain building to shape its surface as the earth's has been shaped. This fact explains the greatest scientific importance of the moon. The moon preserves intact a record of planetary origin and evolution which reaches much farther back than anything preserved on earth. Although the moon and earth formed at the same time, about 4.6 billion years ago, on earth the record of rocks older than about 3.5 billion years has been destroyed by erosion and by continuous volcanism and mountain building. If one compares the moon and the earth as examples of planetary formation, the moon seems to represent a case where its internal thermal engine started, coughed and sputtered a bit, and then flickered out. On the earth, the engine, as it were, started running and continues running to this day, producing the continuing cycles of volcanism, earthquakes, and mountain building than we can read as far back as we can trace the oldest rocks.

The moon is thus an example of what the earth might have been like in its early years, but it has been preserved in a deep freeze, so to speak, for us to examine. For the geologist, this is the real importance of lunar exploration, for the moon is the key to studying the early history of the earth and of the rest of the solar system. To find out where we came from, and perhaps learn a little bit about where we are going, we must go to the moon, for the record on earth has been destroyed.

The results from the Apollo missions have been a tremendous breakthrough in science and in our knowledge about the universe in which we live. It is perhaps inevitable that this great exploration, which made the moon more familiar and better-known, has also, in the public view, made it less mysterious, romantic, and aloof, as one cartoon indicates (Figure 61).

However, to compensate for this loss of lunar romance, the new vantage point provided for man by the Apollo program has made our own earth seem more important and more valuable, a unique life-sustaining planet sharply contrasted against the dead and blasted desert of the moon (Figure 62). And perhaps



"I MUST SAY I WAS FONDER OF IT WHEN I DIDN'T KNOW IT WAS JUST A LOT OF PEBBLES."

Figure 61. Cartoon by R. Weber in the March 5, 1966 issue of The New Yorker Magazine. Copyright 1966 by the New Yorker Magazine, Inc. Used by permission.



Figure 62. Apollo 8 view of the earth, just past half-full, rising over the light highland areas of the moon. NASA photograph AS-8-14-2383.

Apollo, which has taught us so much about the moon, may also have started us thinking in new ways about our own planet, so that we can look at our own "Space-ship Earth" (Figure 63) with new eyes as we return from the moon to grapple with the problems of its life-support systems and wonder about its mission.

Through Apollo, man has made many giant steps for science and for the future (Figure 64). With Apollo 15, we began the J-series missions, which, with their longer stay times, greater mobility, and larger scientific payload, will provide scientific returns eclipsing any of the earlier ones. The results of these later missions will be much more important, because they will be built

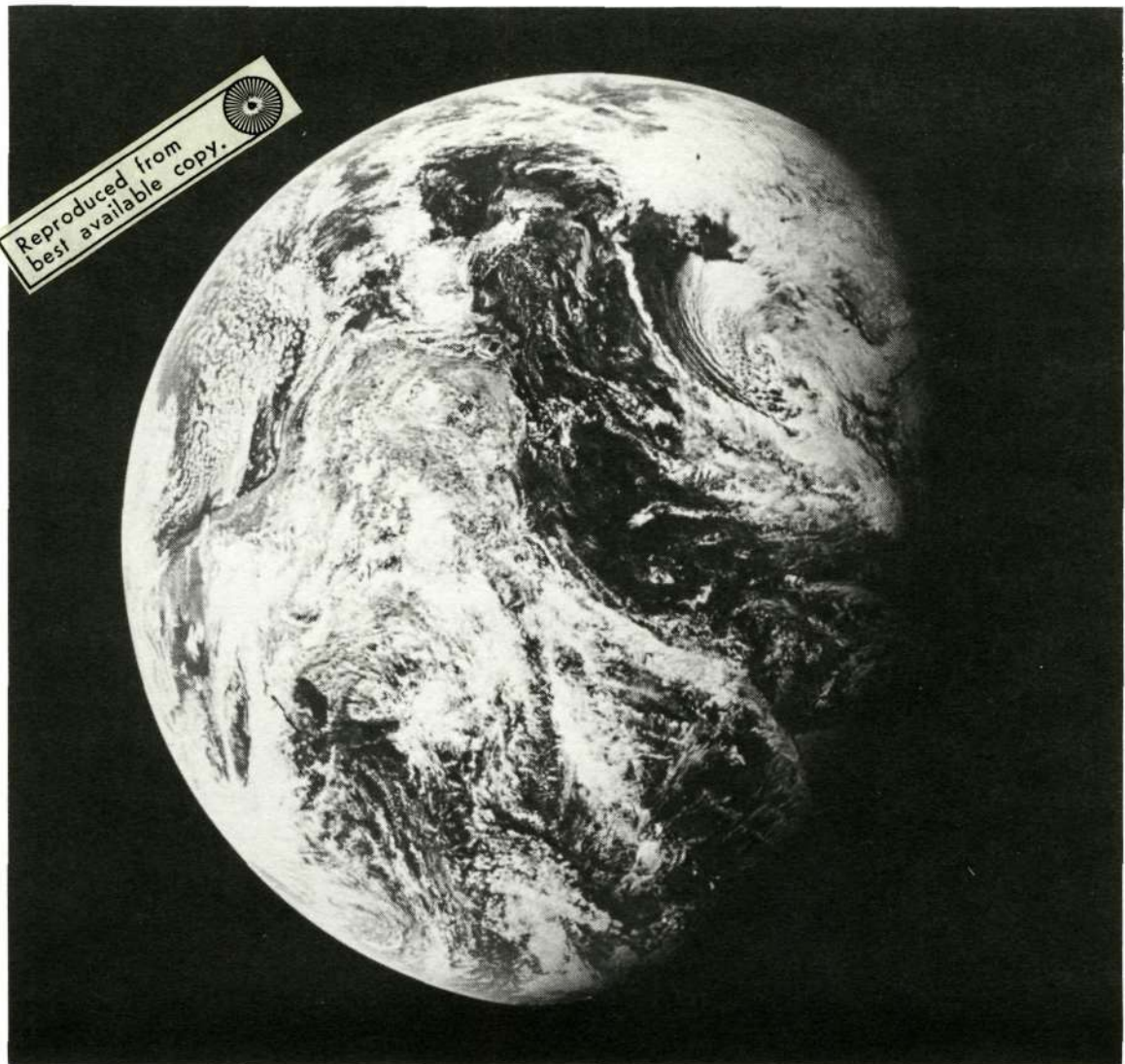


Figure 63. Apollo 8 view of the earth from about 40,000 miles out in space. North America is at the top. South America, largely cloud-covered, is at the lower left, and the bulge of Africa is just visible at the lower right. NASA photograph 68-H-1396.

into the framework of information that has already been returned, each new piece of data fitting into what we have already found out. All the world watched the incredible and unbelievable spectacle of the landing of Apollo 11. But for the scientist, the missions to Hadley Rille, Descartes, and Littrow with which the Apollo program will terminate will be the ones to watch.

As I view the Apollo missions yet to come in the context of all the incredible things that have happened in the last few years, I go back to one of Robert Browning's poems to say what I feel. The knowledge returned from the moon is like Browning's words about life: "The best is yet to be/The last . . . for which the first was made."

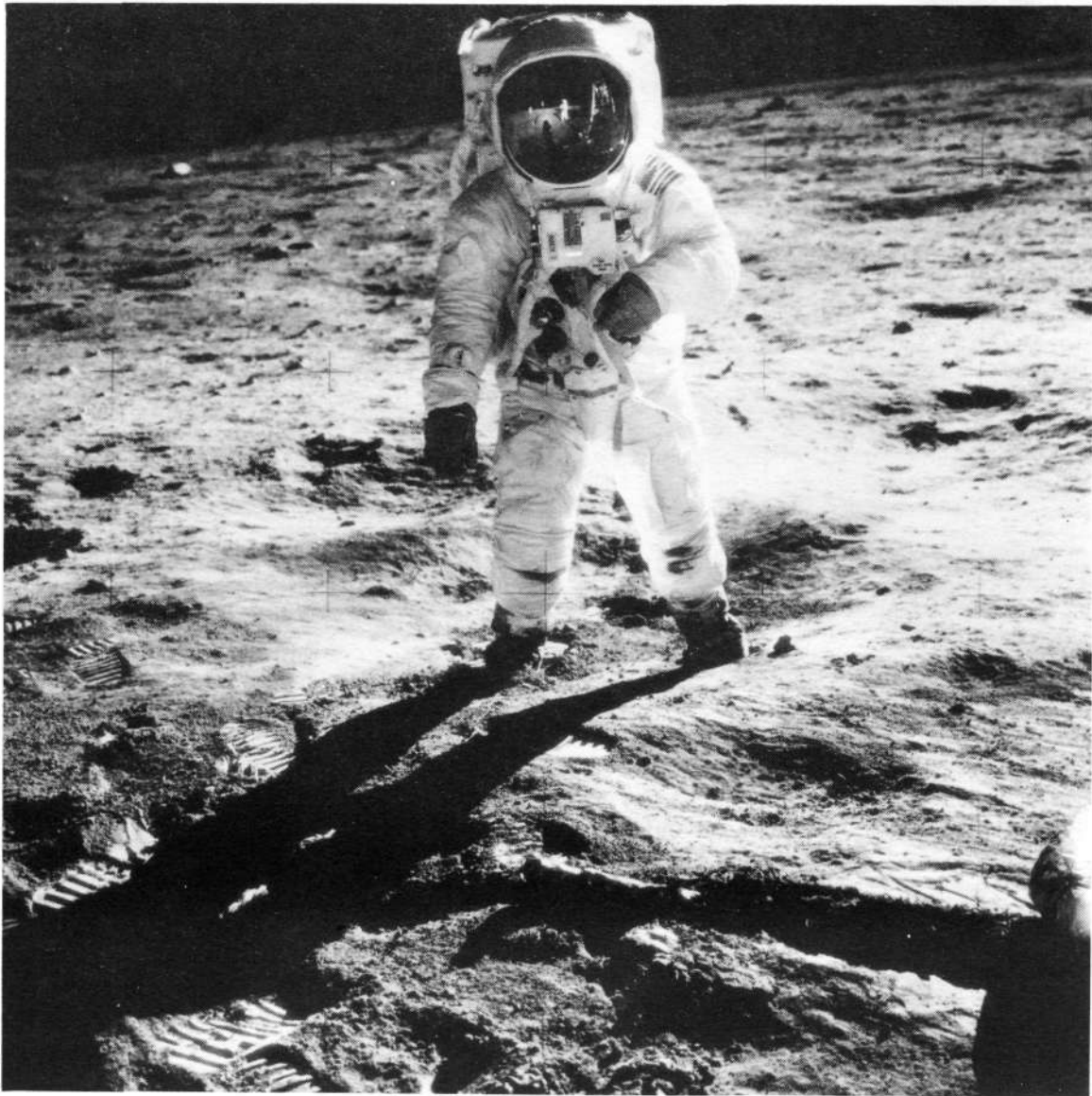


Figure 64. Apollo 11 Astronaut Edwin Aldrin stands on the surface of Mare Tranquillitatis. Reflected in his helmet visor are the lunar module (LM) and the figure of Astronaut Neil Armstrong. NASA photograph AS-11-5903.

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APPENDIX

SOME FACTS ABOUT THE NEW MOON

APPENDIX

Some of the scientific facts that have been learned about the moon as a result of pre-Apollo and Apollo explorations are listed below. The greatest amount of the information has come from the Apollo Program itself, both from studies of returned lunar samples and from data transmitted back by geophysical experiments left on the lunar surface. For more detailed discussion of our knowledge of the post-Apollo "New Moon," see the articles by Hinners (1971) and Lowman (1972) in the Bibliography.

I. ORIGIN

1. The ultimate origin of the moon will probably be more complex than any pre-Apollo theory.

2. Three main theories are still debated for the origin of the moon: (a) separation from the earth (fission); (b) capture by the earth; (c) simultaneous formation of both the earth and moon from the original solar nebula. However, both the fission and capture theories have been weakened by the Apollo results. Several complex versions of the simultaneous-accretion (or "precipitation") theory are now favorably regarded, but the origin is by no means settled.

3. Any theory of lunar origin must now explain the evidence that: (a) the moon apparently formed at the same time as the earth and the rest of the solar system; (b) the moon was apparently heated to very high temperatures, at least to moderate depths (200-400km) during or soon after its formation.

II. HISTORY AND EVOLUTION

1. The moon has existed as an independent body for at least 4.0 billion years (b.y.), which is the age of the oldest rocks yet dated.

2. The moon apparently formed at the same time as the earth and the other bodies of the solar system about 4.6 b.y. ago. Chemical evidence indicates that the material that now makes up the moon must have separated from the solar nebula within 10-100 million years (m.y.) of the time that the elements themselves were formed, at the same time that the material which now forms the earth and meteorites was separating. This evidence includes: (a) traces of the decay products of short-lived "extinct" radioactivities (e.g., Pu^{244}), and (b) the extremely low value of the ratio of $\text{Sr}^{87}/\text{Sr}^{86}$ in lunar materials.

3. The moon underwent considerable geological and chemical evolution during its early years (from 4.6 to about 4.0 b.y. ago), a period of planetary history whose records have been almost entirely destroyed on earth.

4. The moon is not a cold primordial body which has remained unchanged since its formation. Instead, it was hot enough in its interior ($>1200^{\circ}\text{C}$ at 200 - 400 km depth) to melt and produce large quantities of molten lava that now fill the maria.

5. If the moon did form a small iron core in its early history, as some evidence suggests, it must have been even hotter than this at greater depths.

6. The moon remained hot enough to form lavas for a long period of time (at least from 3.7 to 3.3 b.y.) after its formation.

7. The moon has produced different kinds of lavas at different times. The highlands probably contain older Al-rich lavas (4.0 b.y. or older), while the maria contain younger (3.7 - 3.3 b.y.) Fe-rich basalt lavas. There are also chemical differences between the basalts in different maria, e.g., between the Apollo 11 and Apollo 12 samples.

8. The rate of impact of meteorites and larger bodies on the moon was much higher in its early history (4.6 - 4.0 b.y.) than it has been since then. The older highlands are therefore about 30 times as heavily cratered than are the maria. Some of this heavy bombardment may represent the last stages of accretion of the moon from smaller bodies.

9. Despite this heavy early bombardment, much of the original highland crust has been preserved. The regular and widespread layering observed in the Hadley Mountains during Apollo 15 is probably a primary structure in the highland crust (lava flow layers?) that was not destroyed by the extensive bombardment.

10. Large mare basins are found on both sides of the moon, although not all these basins are filled with the dark mare material. These basins were formed by a number of unusually large impacts on the highland crust in a very short period of time. The basins, even the youngest, were apparently all formed before any of the basins were filled with dark mare material (basalt lavas).

11. A significant interval of time passed between formation of the mare basins and the time that they were filled with lavas. During this period, a number of large craters were formed (Archimedes, Sinus Iridum, Plato, et al.). These craters, located near the mare margins, are clearly later than the mare basins because they have not been obliterated, but they are also older than the mare basalt lavas which fill and cover them.

12. Extensive filling of the mare basins occurred almost entirely on the "front" (Earth-facing) side of the moon, with only minor amounts on the "back" side.

13. Some actual dates have been determined for specific lunar features by radioactive-age studies on returned samples. These are: Mare Imbrium impact event, about 4.0 b.y. ago; Mare Tranquillitatis lavas (Apollo 11), 3.7 b.y.; Oceanus Procellarum lavas (Apollo 12), 3.3 b.y.; Copernicus impact, 900 m.y.; Tycho impact (using crater-count studies), 280 m.y. Even fresh features like the ray craters (Copernicus and Tycho) are thus extremely old.

III. BULK CHEMISTRY AND INTERNAL STRUCTURE

1. The moon behaves mechanically like a uniformly homogeneous sphere, unlike the earth which is segregated into crust, mantle, and core, all of which have different densities.

2. However, the near-surface mass of the moon is not uniformly distributed. There is excess mass (mascons) under the circular maria. These mascons are generally believed to be produced by relatively thin layers (10 - 25km thick) of denser basaltic rock under the maria.

3. The mascons have apparently existed since the maria were flooded by basalt (3.7 - 3.3 b.y. ago). Their preservation implies that the moon's upper interior is rigid and fairly strong over long periods of time. (It can support stresses of about 150 atm for periods of billions of years.)

4. The Apollo 15 laser-altimeter measurements showed that the highland areas are as much as 5km higher than the average lunar surface. By contrast, the maria are actually lower and may reach 2 - 4km below the same surface. Total relief between maria and highlands is thus 5 - 10km. Again, this relief indicates that the lunar crust is rigid and strong enough to support these differences in height.

5. The Apollo seismometers have detected "moonquakes." These quakes are weak and infrequent, compared to quakes on the earth. On the moon, about 300 - 400 quakes are detected each year (on Earth, about 1,000,000 per year would be observed). The rate of seismic energy release on the moon is only about 1/1,000,000 that on Earth.

6. The very low level of seismic energy release on the moon indicates that active terrestrial processes such as mountain-building and sea-floor spreading are not occurring on the moon at the present time.

7. Some "moonquakes" are apparently related to tidal stresses and occur near the apogee (farthest point) and perigee (nearest point) of the moon's orbit, where tidal effects are strongest. About 80 per cent of this energy apparently comes from one source about 800km deep. Even the deep moon is therefore rigid enough to build up strain and produce earthquakes.

8. Analysis of seismic signals produced by known impacts of spacecraft on the moon have shown that, over part of the front side at least, the moon is layered and contains different rock types in each layer. This "crust," which is about 65km thick, is divided, on the basis of different sound velocities in the rocks, into the following units:

0 - 2km: rubble and broken rock

2 - 25km: material like the Fe-rich mare basalts

25 - 65km: higher-velocity rock, possibly feldspar-rich like the highland materials.

65+km: still-higher-velocity rock, unlike any common earth rock.

9. The Apollo seismometers have also detected signals produced by meteorite impacts on the moon, which indicates that a continuing bombardment of the lunar surface by fairly large particles is still going on.

10. Remanent (relict) magnetism is found in returned lunar samples and in the lunar crust, implying that the moon at one time (3 - 4 b.y. ago) had a much stronger magnetic field than it does now, a magnetic field possibly as strong as several per cent of the Earth's present field.

11. This magnetic evidence suggests that the moon may, like the earth, have a small iron core which produced the magnetic field. If this idea is correct, then the lunar interior must have been much hotter than previously thought possible.

12. The iron core, if it exists, cannot be much larger than about 700km in diameter. A larger core would produce detectable effects in the moon's orbital behavior.

13. The highlands are lighter in color and higher in elevation than the maria. We now also know that the bulk chemistry of the highland rocks is significantly different from that of the maria rocks, as shown by both returned lunar samples and by the Apollo 15 orbital geochemical experiments. Highland areas are consistently richer in Al than are the maria. This chemical separation may have taken place very early in the moon's history soon after its formation.

14. The Apollo 15 orbital geochemical experiments also indicate that radioactive elements (K, U, and Th) are apparently concentrated in specific parts of the lunar surface. One high concentration is associated with the area around Mare Imbrium, while other areas such as the highlands have generally lower concentrations.

15. All the lunar surface rocks are reduced in volatile elements (e.g., Na, H, Pb, Rb, etc.). This volatile depletion indicates an early high-temperature history. One interpretation is that the lunar material lost its volatiles while condensing from a high-temperature ($\geq 1000^{\circ}\text{C}$) solar nebula.

16. Heat flow from the lunar interior, determined on Apollo 15, is about 3.3×10^{-6} watts/cm²-sec., or about half the value observed on earth. This value was about 3 - 4 times higher than expected. If this value is verified and normal for the whole moon, then the content of heat-producing radioactive elements would be much higher than anyone had previously expected. This in turn would mean an entirely different thermal history for the moon than has been suggested so far. For these reasons, the heat flow measurements on Apollo 16 and Apollo 17 are especially important.

17. Although the upper layers of the moon (to perhaps 300 - 500 km deep) may have been melted, the lunar interior may still be composed of primordial material that has never been melted since the moon formed.

IV. ROCK TYPES AND AGES

1. The youngest lunar rocks collected (Apollo 12 mare basalts; 3.3 b.y. old) are still older than almost all preserved earth rocks. Older lunar rocks (e.g., in the highlands) are probably 4.0 b.y. old or even older.

2. Three basic types of lunar rock materials have been returned: (a) crystalline rocks, such as the mare basalt lavas; (b) breccias, which are more or less compact aggregates of rock fragments, mineral chips, and glasses from a variety of sources; (c) "soil" or regolith, the loose fragmental material that overlies the bedrock.

3. At present, three main types of crystalline rocks have been identified on the moon (through Apollo 15).

a. The highland rocks (oldest), which are Al-rich and probably consist of feldspar-rich basalts, anorthosites, and other minor types.

b. Unusual basaltic rocks, apparently concentrated in the region around Mare Imbrium (Apollo 12 and Apollo 14 samples), about 4.0 b.y. old, and enriched in minor elements such as K, P, and rare-earth elements (REE). The terms KREEP basalt (from the enriched elements) or "nonmare basalt" are used for these rocks.

c. The Fe-rich mare basalts (youngest), (3.7 - 3.3 b.y.), which are not enriched in the same minor elements.

4. The most intensely-studied rocks are the Fe-rich mare basalts which were collected from Apollo 11 and Apollo 12 and which are also present in the Apollo 14 and Apollo 15 samples. The following conclusions have been reached about these rocks and their formation:

a. The common minerals are the same ones found in terrestrial basalt lavas: pyroxene (Ca-Mg-Fe silicate), plagioclase feldspar (Ca-Al silicate), and ilmenite (Fe-Ti oxide). Less common minerals are olivine (Fe-Mg silicate), chromite (Fe-Cr oxide), and cristobalite (Si oxide).

b. The rocks formed as thin flows which cooled and crystallized rapidly at or very near the lunar surface. Cooling times for individual flows were probably a few months to a few years, and the flows themselves were probably a few meters thick.

c. These lavas did not solidify at a single temperature. They began crystallizing at about 1150°-1250°C and were completely solid by about 850°-900°C.

d. As crystallization continued, the composition of the liquid in equilibrium with the crystals changed continuously. In the last stages of crystallization, when the rocks were about 95 per cent solid, the remaining small amount of liquid was enriched in K, Al, Fe, P, Si, and other elements. This liquid solidified to form a "mesostasis" composed of small crystals of unusual minerals which occur between the larger earlier crystals of pyroxene, feldspar, and ilmenite.

e. Small amounts of native iron (Fe) and troilite (FeS) occur in the lavas. These may have formed from a metal-sulfide melt that existed as a separate liquid while the lava was solidifying.

f. The lunar lavas formed under much more reducing conditions (lower partial pressure of oxygen, or P_{O_2}) than do terrestrial basalt lavas. For the lunar lavas, the P_{O_2} was about 10^{-13} atm, and for terrestrial basalts it is about

10^{-5} atm. As a result, the lunar lavas contain reduced metallic iron (Fe), while all the iron in the silicate crystals is in the reduced Fe^{2+} state.

g. Water was completely absent when the lunar basalts formed, and no water-containing minerals are found. As a result, the lunar lavas, even though more than 3 billion years old, are fresh and unaltered, and their crystals are much clearer and better preserved than would be the case in a terrestrial lava flow erupted yesterday.

h. Although water was absent, some gas was present and formed bubbles (vesicles) in the lava as it solidified. This composition of this gas is not known, but it could have contained SO_2 , HCl , CO_2 , CO , F , or Ar .

i. The unusual conditions under which the lunar lavas formed have produced some new minerals, never formed on earth, which are found in very small amounts in the rocks. These minerals include pyroxferroite (Ca-Fe silicate), armalcolite (for Armstrong, Aldrin, and Collins) (Fe-Ti-Cr oxide), and tranquillityite (for Mare Tranquillitatis) (Fe-Zr-Ti silicate).

j. The viscosity (resistance to flow) of the molten lunar lavas is about 1/10 that of terrestrial lavas because of their unusually high Fe content. As a result, the lunar lavas can flow farther while molten than could lavas of terrestrial composition on the moon, and they can form larger crystals while cooling in place.

k. The lunar lavas are chemically unique and are easily distinguished from terrestrial lavas. The lunar lavas are depleted in the easily-lost volatile elements (Na, Pb, H, Rb, et al.), and are enriched in the non-volatile or refractory elements (rare-earth elements, Ti, Zr, Sc, Hf, Y, et al.).

5. The soils and breccias collected from the maria are similar to the mare basalts, but their chemistry indicates that at least one non-mare rock type (enriched in U, Th, and Rb) has been added to them. Small fragments of both anorthosites and the KREEP basalts are found in the mare breccias and soils and are apparently responsible for the chemical differences.

6. In addition, the lunar soils contain small amounts (about 1 per cent or less) of meteoritic material and are enriched in meteoritic elements such as Ni. Observable meteorite fragments are also found in the soil. These results prove that the lunar soil is probably formed by the breaking up of lunar bedrock by meteorite bombardment.

7. The soils and breccias give radioactive "model ages" of 4.4 to 4.6 b.y. This result does not mean that the soils are older than the rocks they formed

from. Instead, this result is apparently caused by the mixing in of exotic material (like the KREEP basalts) which is enriched in radioactive elements. This "age" probably reflects the time of formation of the lunar crust and the separation of its elements into different areas of the moon.

8. No biologically-produced organic compounds have been identified in the lunar rocks, breccias, or soils. No biological activity (either growth of microorganisms or detection of fossil life forms) has been observed. There is no evidence of life in any lunar rock studied.

9. Carbon contents of the lunar rocks and soils are about 50 - 250 parts per million (ppm). The carbon in the rocks probably occurs as minerals (graphite, Fe-carbides, etc.). Much of the carbon in the soils has apparently come from the sun as solar wind and has been trapped in the soil.

V. SURFACE CHARACTER AND PROCESSES

1. The lunar surface is intensely cratered at all scales. Circular craters are observed which are 1 - 500km in diameter (Earth-based telescopic observations), 1km - 1m in diameter (Ranger and Orbiter photographs), less than 1m in diameter (Surveyor photographs), and less than 1mm in diameter (Apollo rock sample surfaces).

2. The lunar craters have probably formed by both meteorite impact and internal volcanic eruptions, although scientists disagree about the relative importance of each process. Certain types of lunar craters are almost certainly volcanic; these include the aligned chain craters, the dark-haloed craters (e.g., in the large crater Alphonsus), and some apparently volcanic cones observed from Apollo 15 orbital photography. Meteorite impact is almost certainly responsible for the small craters (less than about 1km across) which are developed on the lunar surface and for the small micrometeorite craters on lunar rock surfaces.

The origin of larger craters is more uncertain. Many scientists believe that most of the large craters, including the large mare basins (300 - 1000km in diameter), were produced by the impact of very large planetoids. However, volcanic processes can also produce large craters (calderas). To complicate matters further, there is evidence that large impacts can also trigger internal volcanic eruptions, so that the resulting crater forms by both impact and volcanism. The high-resolution Orbiter photography has shown that even "typical" impact craters like Copernicus and Tycho may have originated in such a composite way.

3. The lunar surface is covered by a fragmental surface layer, apparently produced by fracturing and crushing of bedrock by continued meteorite impacts. The layer may be as much as 2km thick over the highlands and is generally 1-10m thick over the younger maria. This "soil" or regolith contains all sizes of particles from boulders down, but much of its material consists of particles less than 0.1 mm across.

4. There is no thick layer of fine dust on the lunar surface. The surface material has the approximate consistency of "wet beach sand," and men and machines can operate on it.

5. The lunar surface material is a very good insulator. The variation in temperature during the lunar "day" (about 200°C) would not be detected below a meter or so deep in the soil layer.

6. There is no erosion on the moon caused by water as on earth. Erosion takes place by continuing meteorite bombardment. Impacting particles range in size from large bodies that form sizeable craters down to very tiny particles less than 0.001mm across that form the small micrometeorite craters ("zap craters") found on exposed rock surfaces. Because the moon has no atmosphere, even the smallest particles strike the surface and erode exposed rocks.

7. Because the moon has no atmosphere, the "solar wind," which consists of elemental particles streaming out from the sun, is trapped in the lunar soil. The lunar soil also traps cosmic rays, and these produce radioactive elements in the surface rocks and leave distinctive microscopic tracks in silicate minerals and glass fragments. By studying these effects in the lunar rocks, scientists can determine: (a) the rates of stirring and overturning ("gardening") of the lunar soil by meteorite impacts; (b) the variation in the intensity of cosmic rays and the solar wind in the past few million years.

8. Studies of the lunar surface processes show that:

a. The rate of erosion by meteorite impact is very slow, about 10^{-6} to 10^{-7} cm/year.

b. Some rocks have remained at or near (within 1 meter) of the lunar surface for long periods of time, as much as 50 - 500 million years.

c. Most of the rocks studied have been exposed at the surface for relatively short periods of time, generally under 50 m.y. Turnover of the lunar soil is therefore sufficiently rapid that a rock at the surface has only a small chance of remaining at the surface for more than 50 m.y. before being broken up or buried.

d. Most of the exposed rocks are destroyed by sudden breaking into smaller pieces by a single large impact rather than by gradual wearing away by many small impacts over a long period of time.